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MICROWAVES AND MICROWAVE OPTICS

By

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CHAPTER I

THE PROBLEM AND DEFINITIONS OF TERMS USED

Every time we open our eyes we observe one segment of the spectrum of electromagnetic vibrations. This spectrum extends from the gamma rays up through what is now called micro-waves, into the radio waves. The light that we see is that part of the electromagnetic spectrum called the visible spectrum and it extends from approximately 4000 to 8000 angstroms. That is, those electromagnetic waves with wave-lengths of from .000039 to .000078 centimeters long are normally visible. Wave-lengths slightly longer than this extend into the infra red band and a band of waves longer than the upper limit of the infra red are called microwaves.

The recent development of Radar and its use of micro-waves as a means of detection and navigation would tend to cause one to lose sight of the fact that the knowledge of the existence of microwaves in the electromagnetic spectrum is as old as radio. The retardation of their development was due largely to two factors: (1) the technology of their production, and, even more significant, (2) their highly directional nature--nearly line of sight--made then practically useless in the conventional "radio" sense. Oddly enough, it was this last aspect of microwaves that eventually led to their development and made them so valuable as Radar in the last war.

I. THE PROBLEM

Statement of the problem. It is the purpose of this study (1) to investigate the production, transmission, and reception of microwaves; and (2) to demonstrate the practicability and advantages of using microwaves to demonstrate optical principles.

Importance of the study. The recent prominence that has been attained by microwaves in the realm of electromagnetic vibrations rivals even that of conventional radio. The fact that much of the work done in this field was kept under the watchful wing of military security leaves the present day scientist interested in this field with a rapidly developing, highly valuable phase of science about which he knows relatively nothing.[1] It is an embro which has grown to manhood under military fostering and even its parents no longer recognize it. The rapid development of this new field in so many phases (such as television) makes it mandatory that its early developments be understood.[2] Isolated facts concerning microwaves which have come to the attention of many people must be shown in a perspective which was not possible before the end of the war.

This paper makes no attempt to cover all, or any single phase of microwave production, transmission, or reception with

1. TIME, Volume XLV No. 12 March 19, 1945 P.54
2. SCIENTIFIC AMERICAN, 172:174 March 1945

any semblance of completeness. In it, the author has attempted to lay the basic groundwork, in a largely descriptive way, upon which a more detailed study can be built. With this groundwork has been integrated a few of the aspects of one practical way which microwaves may be used as a teaching aid, that is, the practicality of using microwaves to demonstrate optical principles.

It is the opinion of many experts that the usual elementary courses in physics do not lay an adequate foundation in the subject of wave propagation. The reason for this is that optical experiments, as such, are not adapted to the task of clearly demonstrating the principles they prove. There are many reasons why these experiments suffer a psychological handicap due to the strangeness, and apparent remoteness from ordinary experience of the subject. Successful experimentation requires a high degree of manipulative skill. And, conclusions cannot be checked by direct measurement.

Microwaves are a medium which offer a clear demonstration of many almost strictly theoretical (as far as the average experimental work is concerned) results. The slits, etc., can actually be smaller than the wave-length without becoming microscopic; or large, relatively, without becoming too unwieldy. The results of optical experiments performed with this apparatus can clearly be shown to a whole class.

II. DEFINITIONS OF TERMS USED

Microwaves. Microwaves are electromagnetic vibrations of frequency greater than one thousand million cycles per second. Thus we see from the equation

$$C = n\lambda$$

where C is the velocity of light of 3×10^{10} cm/sec.

and n is the frequency,

that λ for microwaves is

$$\lambda = C/n = 3 \times 10^{10}/10^{9} = 30 \text{ centimeters}$$

Therefore, microwaves are electromagnetic vibrations with a wavelength of 30 centimeters or less.

Electromagnetic waves. The simplest type of electromagnetic wave is a plane-polarized monochromatic wave. It consists of two sine waves which are in phase with each other but are considered to be perpendicular to each other in their motion. Figure 1-1 (below) is a theoretical sketch of an electromagnetic wave and it should be noted that the electric and magnetic componets of the wave are in phase with each other and that the amplitudes of the electric and magnetic vectors are equal.

In every interference or diffraction phenomenon, the electric waves mutually influence each other in exactly the same way as the magnetic waves. However it is the electric vector that affects the photographic plate and causes fluorescent effects.

Presumably, also, it is the electric vector that effects the retina of the eye in the case of visible electromagnetic waves (light). It appears that the electric component plays a dominant part and the magnetic component, though no less real, is less important.

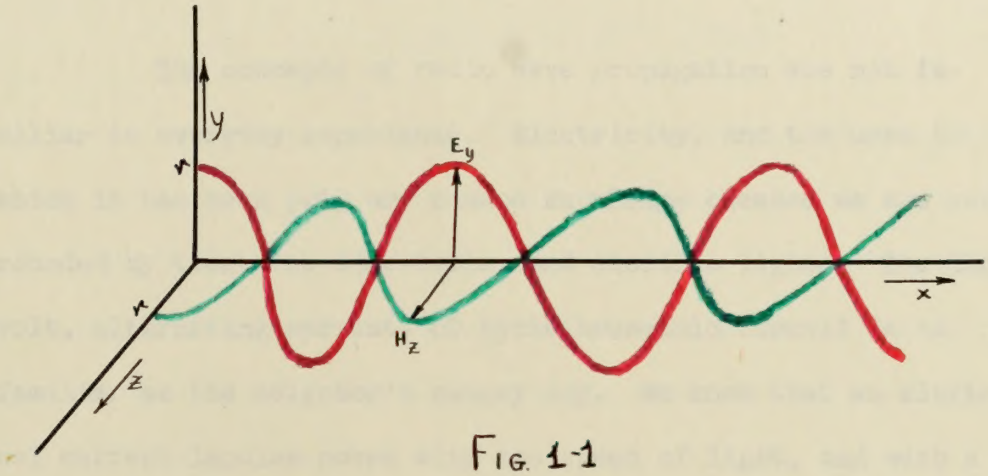
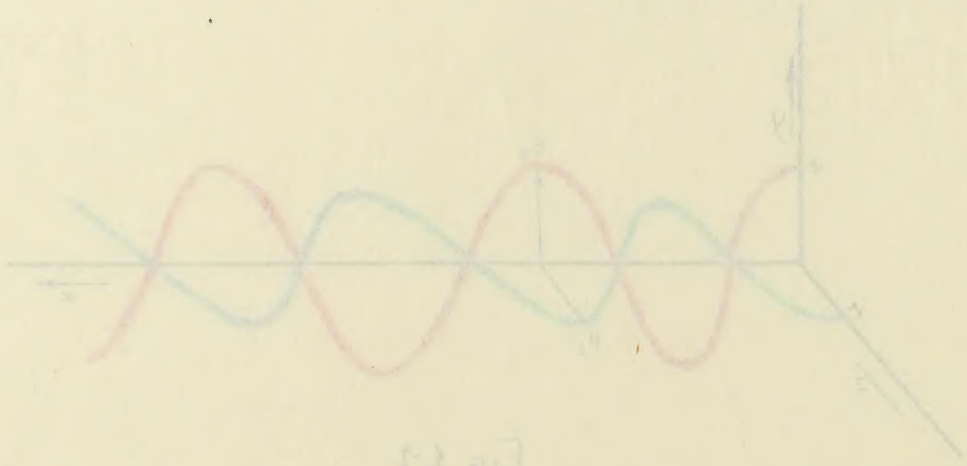


FIG. 1-1

It can be shown that for an electromagnetic wave in a vacuum, the energy of the electric wave per unit volume is $E_o^2/8\pi$, where E_o is the amplitude of the electric wave. Similarly, $H_o^2/8\pi$, is the energy per unit volume in the magnetic wave. Since $E_o = H_o = r$ we have

$$\text{Energy per unit volume} = r^2/4\pi$$

for a wave in a vacuum. Half of the energy of the wave is contributed by the electric vector and half by the magnetic vector. In order to obtain the intensity, we have merely to multiply the above quantity by C, the velocity of the waves, since this will give the volume of the waves streaming through an area of unit cross-section per second. The intensity is consequently also proportional to the square of the amplitude of either the magnetic or the electric wave.



CHAPTER II

INTRODUCTION TO MICROWAVES

I. THE ULTRA HIGH FREQUENCY CONCEPT

The concepts of radio wave propagation are not familiar to everyday experience. Electricity, and the uses to which it has been put, are common knowledge because we are surrounded by toasters, door-bells, and electric lights. The 110 volt, alternating current, 60 cycle household circuit is as familiar as the neighbor's hungry dog. We know that an electrical current impulse moves with the speed of light, and with a simple calculation we can discover that the wave length of our household current is in the realm of 3,100 miles.*

Now, let us imagine that the cyclical rate of the current is greatly increased to a value of one thousand million cycles per. second.** With this cyclical rate, the wave-length is reduced to 30 centimeters. The current now oscillates back and forth so fast that it never has an opportunity to travel very far in one direction. However, the transfer of these electrons is energy and this energy can be made to do work. The ultra high frequency nature of the waves does not make them adaptable

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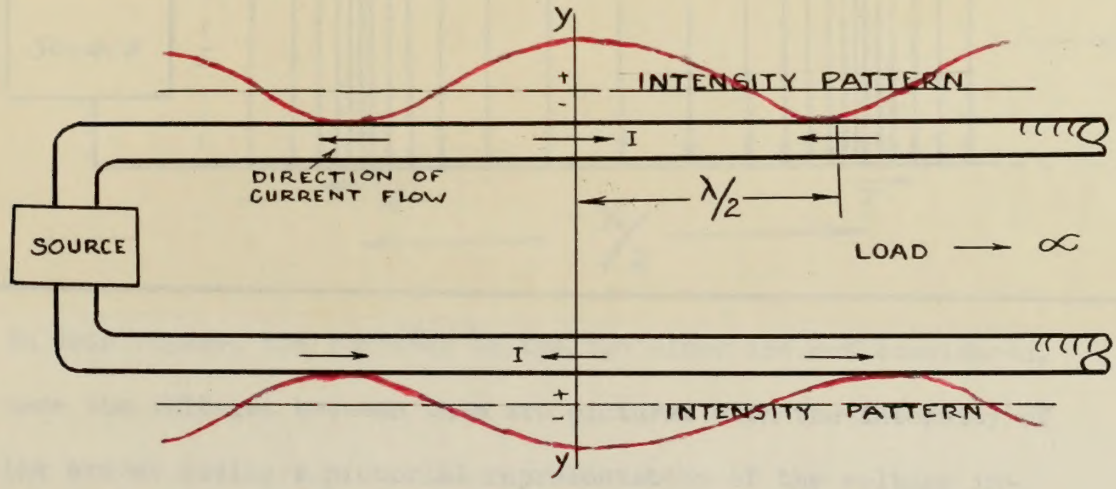
* Speed of light 186,000 miles $sec.^{-1}$/60 cycles $sec.^{-1}$

** One million cycles per second is a megacycle.

for use in running an electric shaver but they are none-the-less important. These brief oscillations of electrons are short radio waves and, when they are 30 centimeters or less, are called micro-waves.

II. PARALLEL-WIRE TRAMISSION LINES

As we have seen, an infinitely long wire carrying alternating current of any frequency will have current flowing in different directions in different parts of it.* Since the system must be closed, the wire must eventually return to the source. When the wire is brought back parallel to itself, the system is called a parallel-wire transmission system. If, as we have assumed, the parallel-wire transmission line is infinite in length, it is easy to see that the currents at any point on a Y-axis cutting the two wires will be equal in intensity and opposite in phase.



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* It must be remembered that the wire may be considered as merely a path guide for the wave motion which, it is assumed, takes place in the space about it.

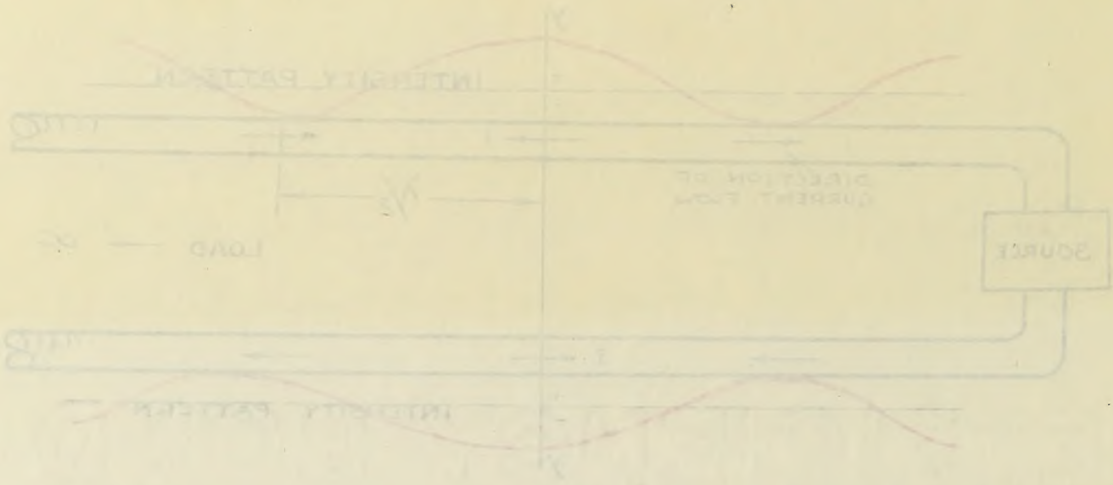
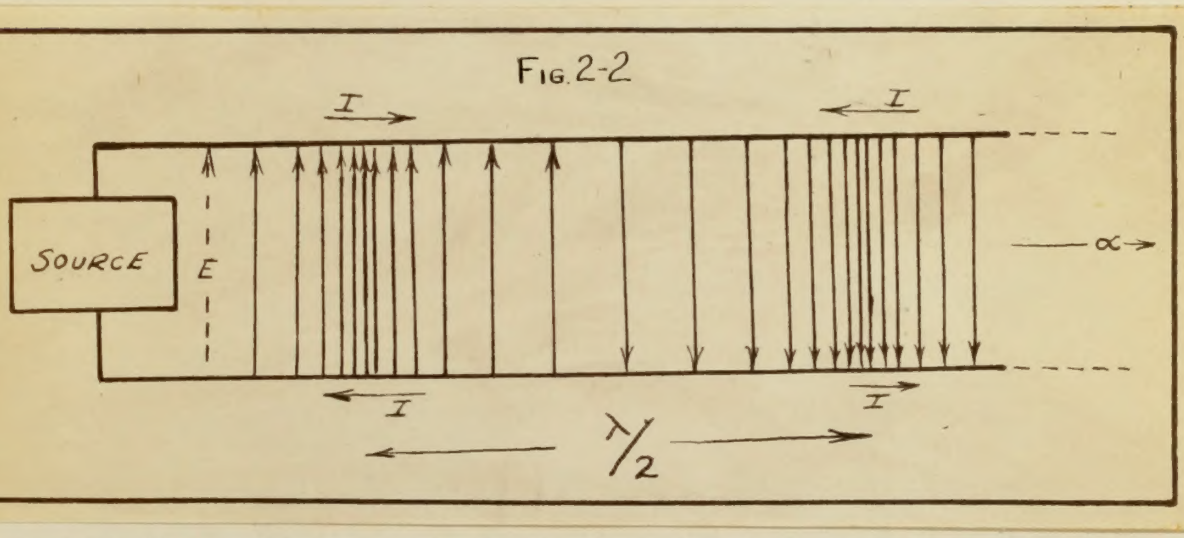

SOURCE

Figure 2-1 shows an instantaneous picture. The red sinusoidal curves above and below the parallel wire transmission lines represent current intensity patterns. When the potential is positive in one wire, the current flows to the right away from the source, as the potential changes, the current decreases and then flows in the opposite direction. At the instant diagrammed, the current in the upper wire, at the point of intersection with the Y-axis, is flowing towards the right while the current a half wavelength distant on either side is flowing towards the left. One half cycle later the situation in this wire is reversed. In the lower wire the current has the same magnitude but is in the opposite phase. An equivalent diagram is given in figure 2-2.

FIG. 2-2



In this figure, the currents in the two wires are not considered. Here the voltages between them are pictured with the intensity of the arrows giving a pictorial representation of the voltage intensity between the two. We said, in connection with figure 2-1,

that the current pattern changes with the frequency or cyclical rate. As the current pattern changes, the voltage pattern between the wires changes and it is a single measurable quantity which moves from the source to the load and does not return. Thus, for the voltage wave motion, there is no closed circuit and none is needed.

A comparison of figures 2-1 and 2-2 clearly shows that it is an unnecessary burden to consider a current flow of one direction in one wire and one of the opposite in the other. It is much easier to visualize the traveling waves and to know that the whole pattern moves from the source to the load.

At all frequencies, parallel-wire transmission lines exhibit radiation losses and act like antennas as well as carriers of energy. These radiation losses become greater at higher frequencies but can be diminished by placing the wires close together. As the wires are placed close together the magnetic fields surrounding each of them become superimposed and tend to cancel each other. The closer together the wires are placed the nearer complete cancellation is attained and the less the radiation because both electric and magnetic fields are necessary in order for energy to move out into space. However, the wires cannot be brought completely together because two separate wires must be used and because some minimum spacing between the wires must be maintained for proper insulation and impedance properties. The minimum space remains essentally constant at higher frequencies

despite the fact that the radiation field, which depends upon the rate of change, becomes more important. For this reason, "it is difficult to build satisfactory parallel-wire transmission lines for operation at frequencies much in excess of 200 megacycles."[3] This upper limit of parallel-wire transmission lines is far short of the lower limit of the microwave frequencies and we must look for some other means for transmitting these ultra-high frequency waves.

III. COAXIAL LINES

In the preceding section of this chapter we saw that open wire transmission lines are of little value for transporting microwave energy because radiation makes them useless. There remains the possibility of transmitting microwaves by coaxial lines and by waveguides, both of which can be used with ultra-high frequency. The function of coaxial lines can be explained without the use of the field concept but waveguides are best understood in terms of traveling waves of electric and magnetic fields and will be discussed in a later chapter. What can be said about coaxial lines, can, in general, be applied to open-wire transmission lines. However, the brief discussion that follows is specifically restricted to the coaxial line case, because it is then only applicable to microwave transmission.

3. V. J. Young, UNDERSTANDING MICROWAVES (New York: Rider Publishing, Inc. 1946), 5P.

As the term implies, coaxial cable is composed of two members, the inner conductor being enclosed in a tube formed by the outer conductor. By the use of such a transmission line, one of the three distinct types of losses encountered in the transmission of very high frequency electrical energy is eliminated. There is no radiation from the line because there is simply no way for the radiation to get out. The other two types of losses are; (1) losses due to impedance mismatch, and (2) losses due to heat.

The losses due to impedance mismatch are usually associated with the impedance mismatch of the line either at the source or at the load. However, mismatching may occur in the line itself if the line is not perfectly uniform along its length. When we speak of mismatching, interest is focused on a property of the line called characteristic impedance and both the source and the load should be matched to that impedance since maximum electrical power is always fed from one device to another when the impedances are equal. In principle, this match may be made by means of variable transformers at both source and the load.

The current waves in the center conductor of a coaxial line are always just 180 degrees out of phase with those of the shield. However, there may be a phase difference between the instantaneous voltage and current. Since the instantaneous product of the voltage and the current is the instantaneous power, the greater the phase angle between these two, the greater the mismatch.

Another case of line loss occurs in coaxial line when two voltage waves travel in opposite directions along the same line. When the reflected wave is equal to the transmitted wave the voltage becomes zero and such a case might be called a perfect mismatch. This situation would occur if the load end of the line were open or shorted.

The fact that a perfect mismatch occurs when the load end of the line is open or shorted is often of great practical importance in coaxial transmission lines. Some of these lines use air as a dielectric between the center conductor and the case and some method of support for the center conductor must be found. One practical solution to this problem is offered in the stub support method

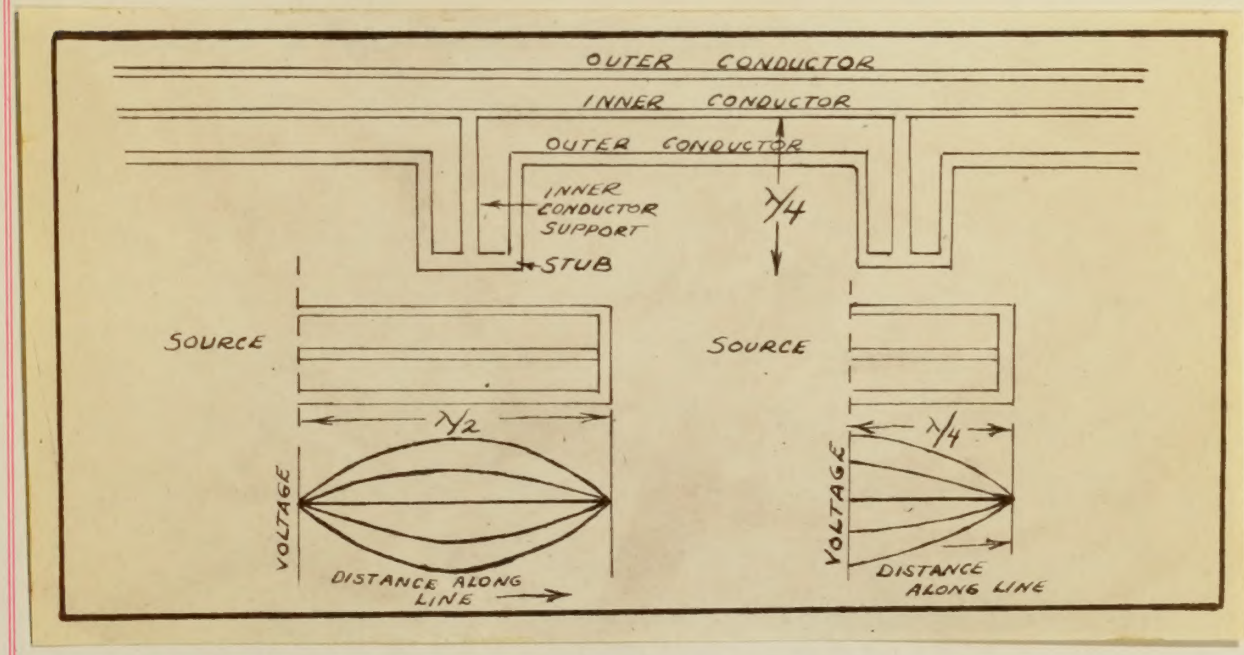


FIG. 2-3

In the case of the half-wave stub support, the shorted end has no voltage so one node appears at this point. One half-wave length away there is another voltage node and this node occurs at the point of intersection of the stub with the inner conductor. Since there is a node at the inner end of the stub, no voltage can be impressed across this end. The resistance at this point is a constant, however, and, because of the voltage drop, the current tends to approach infinity. An increase in current means a power (I^2R) loss at this point.

In the quarter wave stub, the situation is quite different. As in the case of the half-wave stub, one end is shorted and the reflected wave is equal to the incident wave. No voltage appears at the shorted end so this is the position of a node. Any voltage can be impressed on the unshorted end but no power is absorbed.

At the instant of the beginning of energy transfer in the line, there is a slight loss of power at the quarter-wave stub because there is an initial current flow in this member. This is only an initial loss and any further transfer of energy in this line encounters no power loss here because the stub presents a greater impedance to the energy flow than the conductors.

The other type of loss encountered in coaxial line is the loss caused by the heating of the conductors due to their finite resistance through which the current must flow. If an instantaneous picture could be taken of the charges in a segment of coaxial cable, it would be seen that the charges are massed largely on the outside

of the inner conductor and on the inside surface of the shield. This phenomenon is called the skin effect.

It is necessary to determine the extent of penetration of the energy into the outer conductor for two reasons; (1) the shield must have the necessary dimensions to prevent any total energy penetration which would result in radiation losses; (2) the effective volume of the metal through which the current must flow must be determined ~~so that the effective volume of the metal through which the current must flow must be determined~~ so that the effective resistance and the I^2R loss generating heat can be calculated. If we think in terms of electrons, the problem resolves itself into the determination of how deeply an electron of the conductor must be embedded in its surface to be unaffected by the current and voltage waves traveling down the line.

"It develops that it may be assumed for many calculations (especially when the frequency is very high) that all the skin thickness δ where

$$\partial = \sqrt{\rho/f} \text{ cm.}$$

in which ρ is the specific resistance of the material expressed in electromagnetic units, and f is the frequency of the energy being transmitted. Actually, of course, this is not true. Currents do not flow uniformly for just this depth and then suddenly cease. Instead they fall off exponentially with penetration. It is just that δ has been calculated as the depth at which the current falls off to the proper value (off to $1/\varepsilon$ times the maximum, where ε is the base of Naperian logarithms or about 0.4 times the maximum value), so that all currents flowing at greater depths added to those at lesser depths, gives the equivalent of the average current flowing in the skin alone."[4]

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4. IBID, P74

One conclusion that may be drawn from the equation given above is that as the frequency goes higher, the charge is concentrated more and more at the surface. Thus, we can say (however, only with some fear of oversimplification) that higher frequencies increase the skin effect and thereby increase losses due to heating. (In the equation given below it will be seen that a decrease in δ will result in an increase in r .)

Now to return to the general problem of making the loss of energy in a coaxial line as small a fraction of the power transmitted as possible, we see that the skin effect will influence the dimensions chosen for the line. If the line is properly matched, the impedance is Z_o. The measure of the power dissipated in the line is I^2r when r is the resistance of the line. The problem, then, is to minimize I^2r/I^2Z_o or r/Z_o. The resistance r may be calculated in the usual manner:

Resistance = specific resistance x length /area

$$r = \rho \times l/2\pi a\delta + \rho \times l/2\pi b\delta$$

where ρ is, as before, the specific resistance, l the length of the line, and a and b are the radii of the inner and outer conductors respectively.

The calculation of the value of Z_o is somewhat more complicated and cannot be shown in detail here. However, it turns out that when air is the dielectric, Z_o depends only on the ratio of the sizes of the inner and outer conductors.

$Z_o = 138 \sin b/a$ ohms.

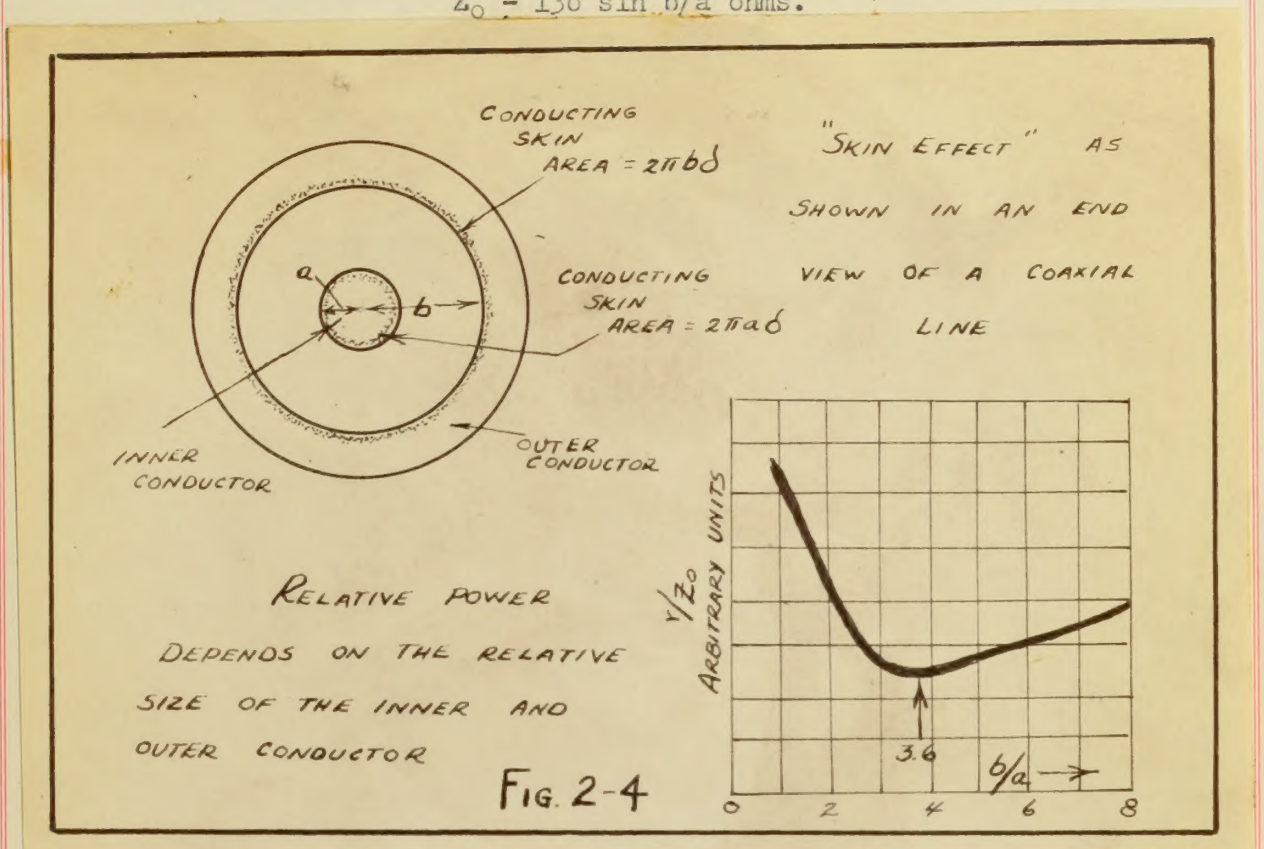


FIG. 2-4

As shown in the graph in Figure 2-4, the minimum value of r/Z_o occurs at the point on the b/a axis where the ratio between their radii is 3.6. Since the curve is rather flat at this point, slight variations from a ratio of 3.6 for the radii of the inner and outer conductors will be unimportant. However, large variations from the optimum value will result in an important increase in the dissipative loss.

We have discussed in this chapter why conventional parallel-wire transmission systems are not effective for transmitting ultra-high frequency waves. We have also talked about coaxial transmission lines as a successful means of transmitting microwaves and have discussed the losses encountered in these lines. Now we turn our attention to waveguides as a means of transmitting microwaves.

CHAPTER III

WAVEGUIDES

In the previous chapter we saw that coaxial lines may be successfully used to transmit microwaves. However, when solid dielectrics are used to support the center conductor, leakage is always present to some extent, and, over distances of more than a foot or so, the leakage increases to such an extent that it becomes quite serious. As previously mentioned, stub supports minimize leakage loss but, especially when bends or more complicated fittings are needed, the fabrication difficulties are very great. It is obvious that if the center conductor could be done away with, the difficulties mentioned above would no longer exist.

The transmission of microwaves is accomplished, in many cases, by means of a hollow pipe, or wavequide, much the same as is used in conducting water. Because these waveguides contain no inner conductor which would correspond to a wire within an insulator, it is difficult to understand how a closed circuit is accomplished and, therefore, how the device can operate.

Currents do exist in such a system but they are seldom mentioned because of the difficulty of making a direct measurement of a current which is spread uniformly over a metallic surface. The charge in the metal moves from the bottom of the conductor to the top and down again. As the radiant energy flows through the wave-

guide, the pattern of current flow moves along from the source to the load and the places where the current is moving upwards or downwards is always changing so at any given point on the waveguide, the charge is alternately moved up or down. It must be remembered,

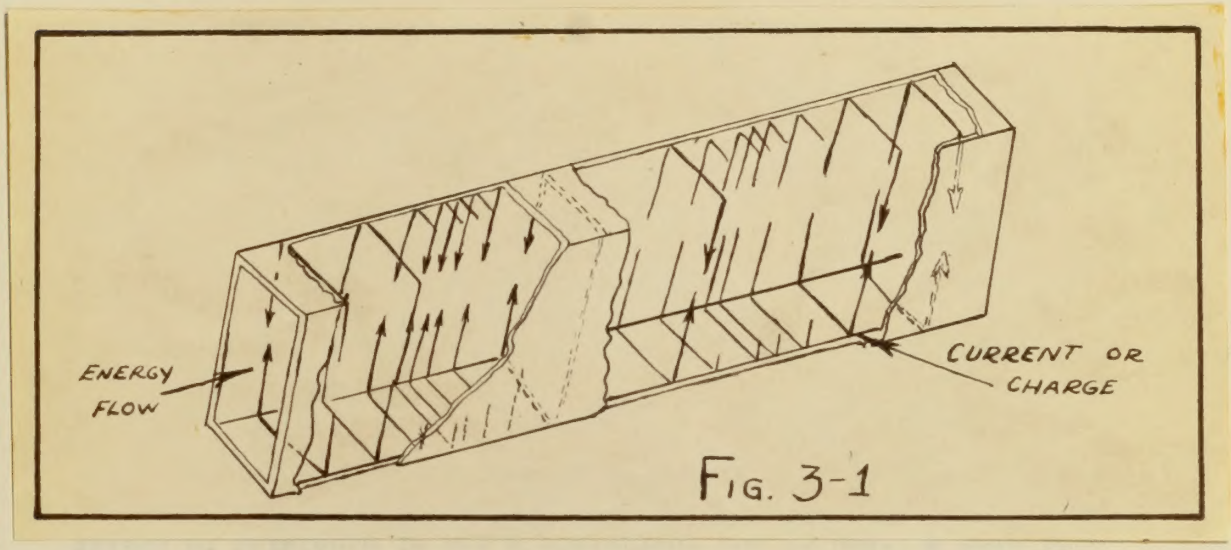


FIG. 3-1

however, that the motion of electrons in the waveguide itself takes place with the energy flow. This flow of energy is often visualized as being similar to the action of radio waves as they alternately bounce off the layers of the ionosphere and the earth or like a golf ball bouncing from top to bottom along the waveguide.

While the analogy of a golf ball bouncing down the waveguide is useful as a simple explanation of the flow of electromagnetic energy in a waveguide, it remains that, for a more complete understanding, the energy should be closely identified with the motion of its electric and magnetic vector.

I. THE ELECTRIC AND MAGNETIC FIELDS

When we talk about conventional current, we use such terms as volts and amperes to recognize and define it. This procedure is in accordance with the best scientific procedure of explaining and defining terms in the simplest correct way. It is only natural, when two explanations are possible, to use the one which offers the easier solution. Thus, one seldom talks of electromagnetic fields in connection with conventional current because this system is not well adapted to explaining the phenomena encountered. However, when we speak of the operation of a particular piece of microwave equipment, we find that the volt, ampere, system of reference is not a convenient one to use. A more successful method of analyzing the flow of energy in a waveguide is offered by the E and H system of analysis.*

Essentially there is no more difficulty in visualizing how the electric and magnetic vectors transfer energy from the source to the load than there is with charge and voltage. It is usually only a lack of familiarity that makes this system seem more difficult.

There are at least two advantages in visualizing energy propagation in terms of electric and magnetic fields. (1) No

---

* E represents the electric vector in an electromagnetic vibration and is in statvolts per cm., H represents the magnetic vector and is in oersteds.

return path is needed so no circuit (in the conventional sense) exists and it is only necessary to trace the electric and magnetic fields from the load to the source. (2) Field quantities, unlike currents, can travel through a vacuum or a dielectric.

II. WAVEGUIDE DESIGN

Waveguides may be rectangular, oval, or round in cross section. However, rectangular waveguides are the simplest and most common and it is this type that will be discussed for the most part, although a great deal of the following information may be extended to guides of other shapes.

Figure 3-2 shows how the dimensions of a given waveguide are decided upon. It is an example of the development of a simple type of waveguide and may serve to bridge the gap between transmission lines and waveguides, although they operate on different principles.

A quarter-wave resonant stub added across a section of two wire transmission lines are shown at left. The point at which the wire stub is connected to the transmission line is a point of high impedance and, as a result, the stub will have a negligible effect on the line. An infinite series of these stubs is shown in the center of Fig.3-2 and this series results in a continuous pipe of rectangular cross-section, or one type of waveguide (Fig. 3-2 right).

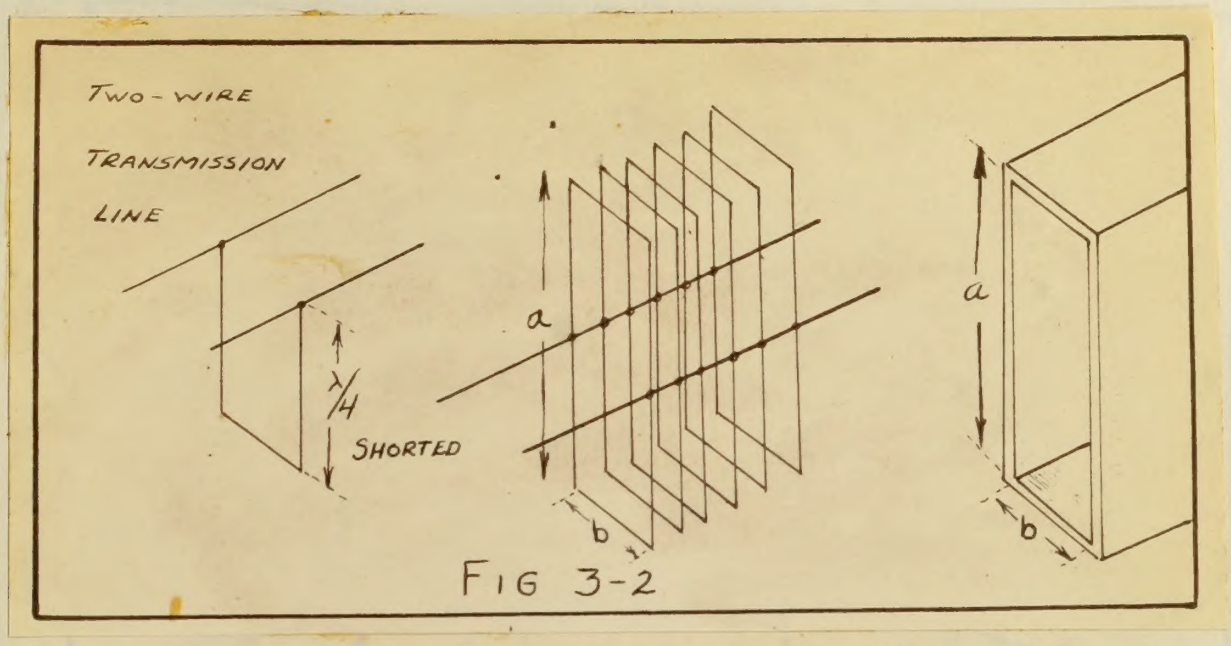


FIG 3-2

Thus, the dimension "a" of this type of rectangular waveguide has a minimum dimension of half a wave-length (in order to propagate a signal) but it may be greater. The dimension "b" is not critical except as will be seen later.

Since reflections back inside the waveguide occur whenever there is any sudden discontinuity such as a change in shape or size (among other things), it is very important that tapered sections be used to connect waveguides of different size. It is also advisable to avoid bends in the guide which have too small a radius of curvature. Right-angle junctions, of course, cannot be used.

In general, there are two types of waveguide bends. They are known as the "E-bend" and the "H-bend" and Figure 3-3 gives example of both. As may be noted from the figure, in the

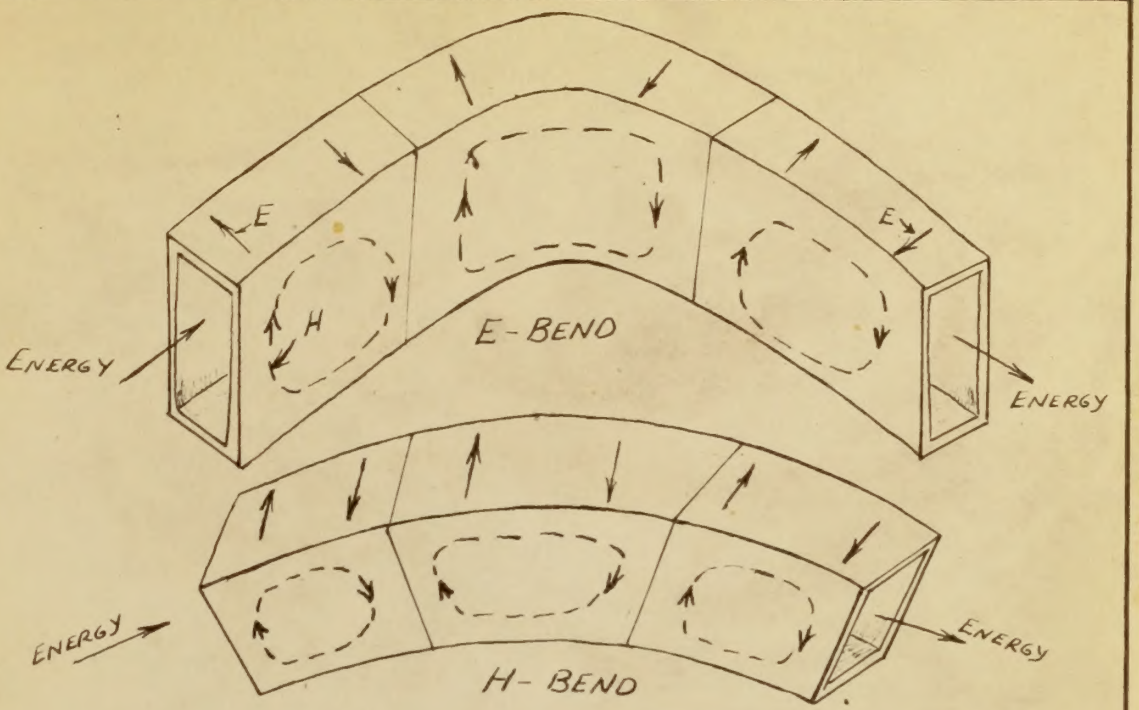
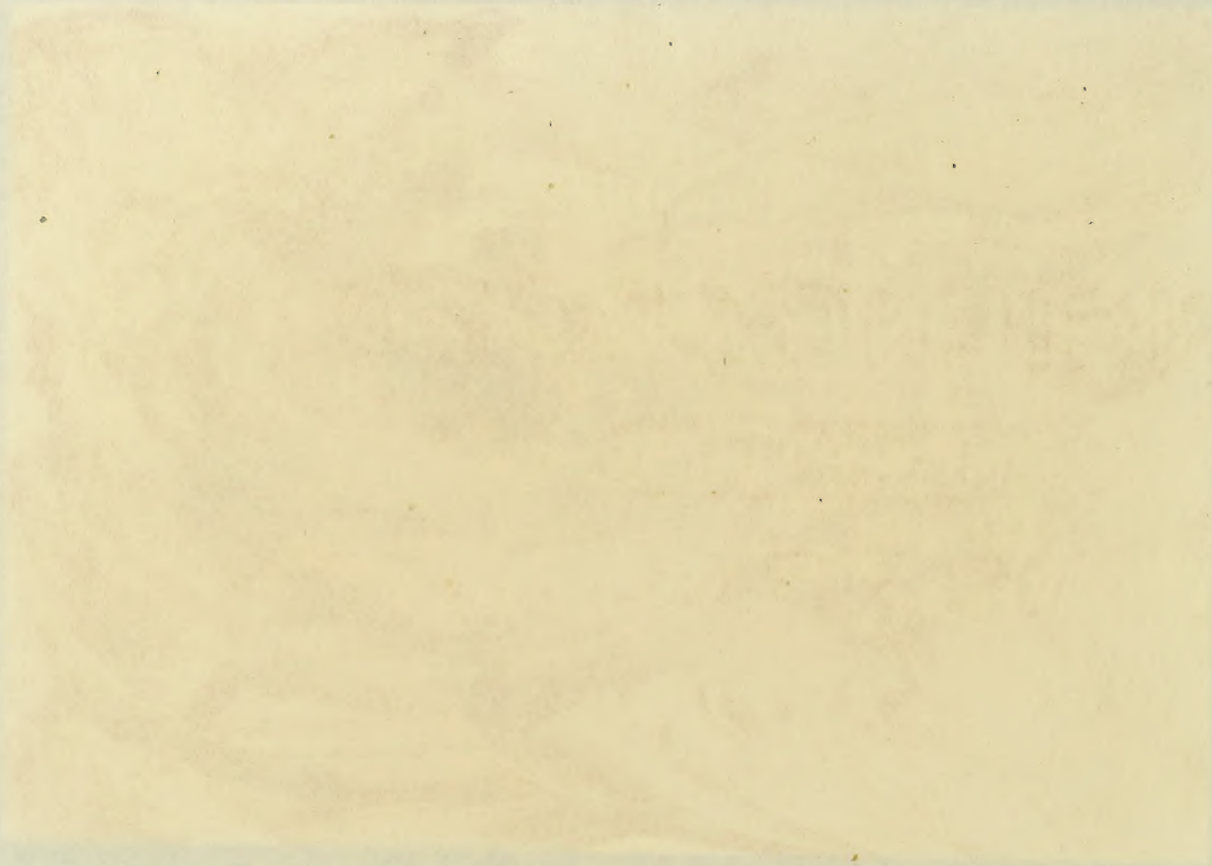


FIG. 3-3

E-bend the electric vector is forced to change its angle which, in the H-bend it is not. In the H-bend, the opposite is true and it is the transverse component of the H-field which is forced to turn as it proceeds along the waveguide.

Theoretical losses due to such bend junctions are almost negligible even if the radius of curvature is only a few times as great as the wider dimension of the waveguide. Actual experimental values of the losses in these bends turn out to be somewhat higher than the calculated losses however. This is probably due to the mechanical difficulty of making truly smooth bends and some reflections do occur at points along the bend as well as at the joints.



However, even these experimental losses are small and bending a waveguide is generally considered an easy and efficient way to turn a corner for both E- and H- bends and circular waveguides as well as other types.

III. WAVEGUIDE FIELDS

In general, when crossed electric and magnetic fields are introduced at the source end of a waveguide they will automatically attempt to transfer energy into the guide. If the load end of the waveguide is perfectly matched, the H contours of the energy will move down the pipe like a series of smoke rings, while the electric lines will radiate out from the center of the pipe and will be distrubuted in time (and, therefore, in distance along the pipe) according to the sine-wave form of the imput voltage. However a number of factors effect the shape of these fields and the various types of transmission are called modes of propagation. The particular mode that might exist in a given waveguide would depend on the method of excitation and the shape and dimensions of the guide. This topic will be discussed more fully in section IV of this chapter.

As we have said, there are many different types or modes of propagation. However, in a rectangular waveguide, one mode (the $TE_{1,0}$ mode) is generally superior to all others. A waveguide in which this type of propagation is possible is one in which the

narrow (or"b" dimension is less than one-half wavelength, and the wide (or"a") dimension is greater than a half-wave length but less than a whole wavelength. An example of the $TE_{1,0}$ mode is given in Fig. 3-4 along with other possible types.

IV. TYPES OF PROPAGATION

The terminology used in naming the various modes of propagation looks rather complicated at first glance but it is not all hard to understand. In general, either the electric or magnetic field will have no component along the length of the guide and it is this fact that is responsible for the first two letters in the naming of waveguide modes.

The letters "TM" refer to transverse-magnetic and in "TM" propagation, there is no magnetic field in the direction of propagation down the tube. The magnetic propagation is transverse. The letters "TE" refer to transverse-electric and signify that the electric field is transverse and has no longitudinal component in the direction of propagation. The first subscript is used to tell the number of half-cycle patterns which exist along the wide edge, and the second number describes the same thing for the narrow edge. The subscript numbers are needed because there are numerous modes of operation (or oscillation) depending upon the cross section of the hollow metal tube and on how it is excited from the r-f* source.

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* r-f = radio frequency

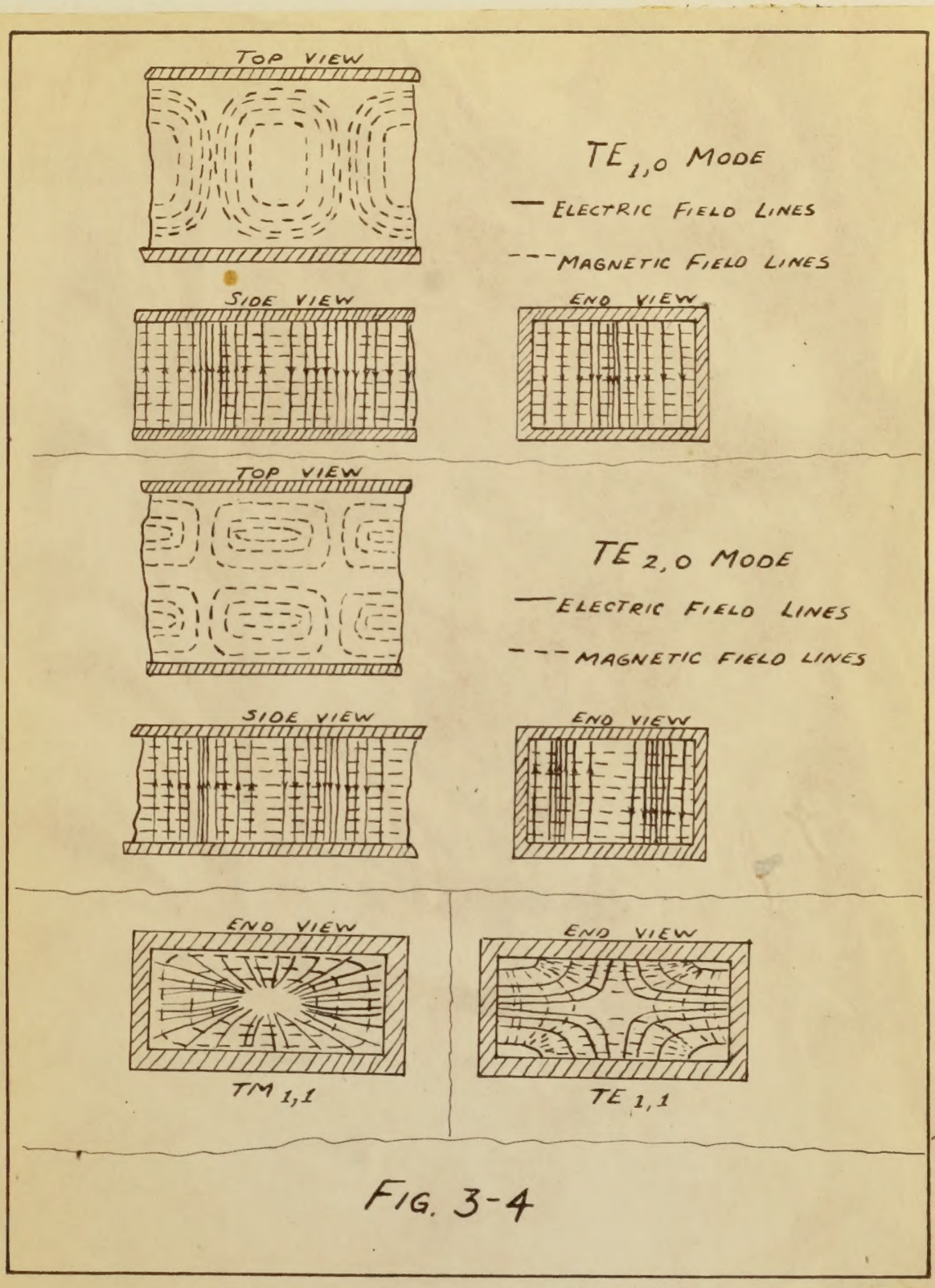
TOP VIEW
SIDE VIEW
END VIEW
TE 1,0 MODE
— ELECTRIC FIELD LINES
--- MAGNETIC FIELD LINES
TOP VIEW
SIDE VIEW
END VIEW
TE 2,0 MODE
— ELECTRIC FIELD LINES
--- MAGNETIC FIELD LINES
END VIEW
TM 1,1
END VIEW
TE 1,1

FIG. 3-4

V. THE TRANSMISSION OF ENERGY IN WAVEGUIDES

There are two requirements that must be met in order for electromagnetic fields to be propagated down a hollow metal tube or waveguide. These conditions are; (1) the frequency must be high enough and, (2) the fields must have certain definite distributions.

A given waveguide will not transmit energy whose frequency is below a certain value. This lower frequency limit is known as the cut-off frequency. If the guide is just a half a wave length in width (dimension "a"), the wave will reflect back and forth across the guide and will make no progress (hence cut-off frequency).

The velocity of the r-f energy in a waveguide is always slower than in air. This is due to the fact that the wave is reflected from wall to wall and does not travel straight through the guide. The group velocity varies with the tube dimensions (dimension "a" in a rectangular guide) and with the frequency. This velocity is always less than the speed of light and increases as the wavelength becomes shorter because there are fewer reflections from the waveguide walls for a given amount of forward travel. (See Fig.3-5 (a)). As the wavelength becomes longer and approaches the cut-off frequency there are more reflections from the wave-guide

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walls for a given amount of forward travel and, therefore, the group velocity decreases. (See Fig. 3-5 (b)).

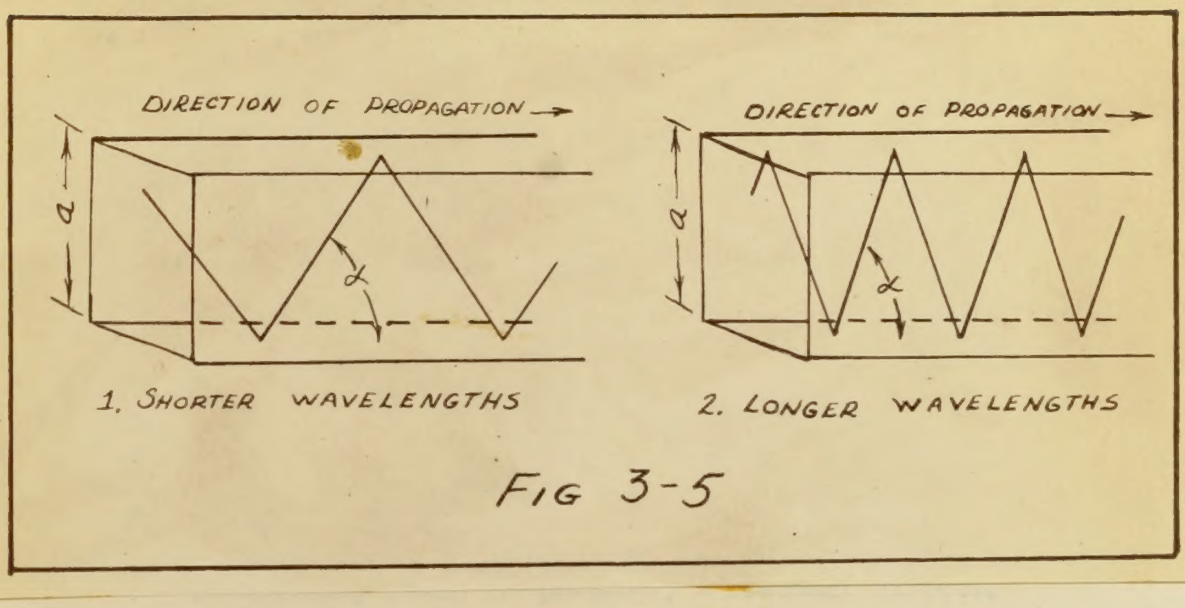

FIG 3-5

The attenuation in a rectangular waveguide of a given size increases as the wavelength of the signal increases towards the cut-off value. This happens because there are more reflections which result in higher losses due to the r-f currents in the "skin" of the inside wall. If the wave-length becomes very short, the attenuation again increases because of an increase in the "skin effect" at higher frequencies.

CHAPTER LV

THE PRODUCTION OF MICROWAVES

As we have seen in the previous chapters, microwaves are ultra-high frequency electromagnetic waves and we have discussed how this energy can be transmitted by coaxial lines and by waveguides. It is the purpose of this chapter to investigate the means of producing these microwaves.

I. THE FUNCTION OF RESONANT CAVITIES

At ordinary radio frequencies, a resonant circuit, consisting of lumped values of inductance, capacitance, and resistance, accomplishes at least three things: (1) it fixes the frequency at which the oscillation takes place, (2) it acts as a storage place in which r-f energy can initially accumulate and build up to a high voltage, and, (3) with the circuit of the oscillator, it provides feedback to the grid in proper phase and impedance so that the oscillation will be maintained. The function of a resonant cavity is analogous to that of a resonant circuit. However, there are fundamental differences between the two and the analogies should not be carried so far that the advantages of cavity resonators are not seen.

II. THE DETERMINATION OF FREQUENCY IN RESONANT CIRCUITS

As we stated above, resonant cavities are much the same in function as resonant circuits. A brief discussion of a resonant circuit such as the Hartley Oscillator (Fig. 4-1) follows:

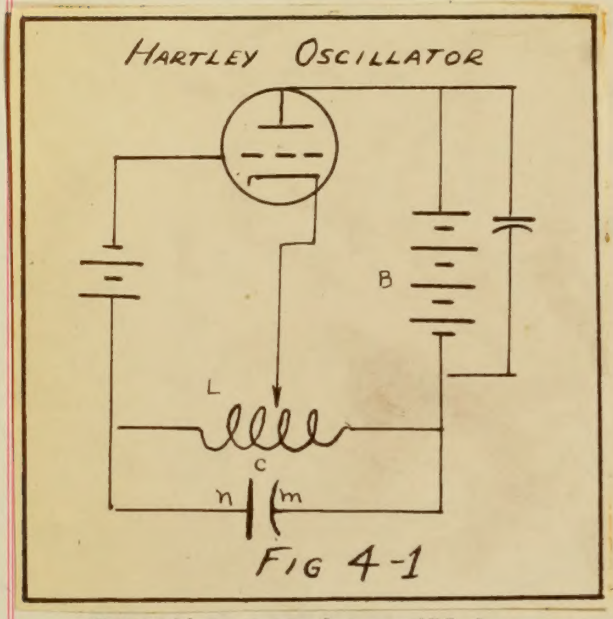

FIG 4-1

Let us assume that, originally, there exists a charge on plate "m" of the lumped capacitance C. This charge will flow through the inductance L to the plate "n" where it will be urged by crowded conditions there and by the field around the inductance to flow back through L to "m". Here the procedure will be reversed and a situation of oscillation will exist. In addition, the plate circuit of the oscillator tube is regulated by the grid in such a way that the oscillating charge in the tank circuit is given a "push" at just the proper point in each cysle. The situation is analogous to a pendulum which, once set in motion, can be caused to have a greater and greater amplitude by a slight impetus at the proper point in the cycle. The amplitude of the oscillation will increase until a load, either intentional or accidental, appears and drains off energy as fast as the B-battery can supply it. As the voltage of the resonant circuit increases,

this condition prevails because this increase causes the amount of power flowing into the external load to get larger until the increasing oscillation strength becomes equal to the power from the vacuum tube circuit.

The frequency of the oscillation is determined by the size of the condenser and the inductance according to the equation,

$$f = 1/2\pi\sqrt{LC}$$

The strength of the oscillation in a Hartley oscillator is limited by the ability of the resonant circuit to store the energy it receives as well as by how much energy is fed into the oscillation by the vacuum tube. A factor expressed by Q is a sort of reciprocal measure of the friction of the oscillator and thereby expresses the ability of the resonant circuit to store the energy it receives.

"When the Hartley oscillator is first turned on, only a small amount of charge travels back and forth from condenser plate to condenser plate. As cycles elapse and additional energy is admitted to the tank circuit by the tube, the oscillating current grows and it would continue to do so indefinitely if it were not for losses in the resonant circuit itself, and from it into the load. The Q of the circuit is a measure of the degree of freedom from such losses."[5]

The oscillation is first built up by having energy fed into the circuit at the proper time in each cycle by battery B. In order that this might be accomplished, the oscillation is allowed to affect the grid of the tube in such a way as to apply voltage across a portion of the inductance at just the right moment in each cycle.

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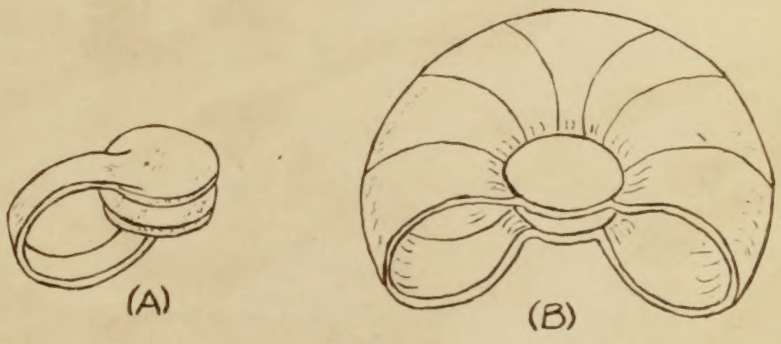
5. Ibid p.172

III. THE DEVELOPMENT OF A RESONANT CAVITY

We have seen how a resonant circuit depends on the action of a condenser and an inductance arranged as a tank circuit. If we were to start to build such a circuit starting with a single loop of wire and a condenser (Fig 4-2 (a)) we would have a resonant circuit of a fairly high frequency but still well below microwave frequencies. The frequency would be increased by



THE DEVELOPMENT OF A RHUMBATRON RESONANT CAVITY (B) FROM A SINGLE TURN OF WIRE AND A CONDENSER (A)

FIG. 4-2

decreasing the size of the loop but the losses would become great and the size of the loop practically infinitesimal before microwave frequencies could be reached. However, the inductance of the loop could be reduced by adding other loops in parallel with it as shown in Fig 4-2 (b). In the limit of such additions, a doughnut-shaped cavity will be formed and such a cavity is called a rhumbatron cavity.

In this section we have seen how a resonant cavity might be thought of as developing from the concept of current flowing back and forth from one plate of a condenser to the other through an inductance. However, a word of caution should be injected here. The concept of inductance and capacitance is used simply as an analogy and only as a matter of convenience. The roles of capacitance and inductance in a resonant cavity are nowhere near as simple as this discussion might imply. Capacitance effects exist between the various loops of the inductance as well as between the plates of the condenser. These effects are important and must be included in any calculation if the calculation is to be valid. Resonant cavities are much more versatile devices than this method of presentation would imply. The shapes they can assume are many and varied and the rhumbatron design is only one. In most of these there is apparently no correspondance in current flow to the charging and discharging of a condenser through an inductance.

IV. FORMS OF RESONANT CAVITIES

The three general types of resonant cavities can be differentiated by means of their general physical construction. The first of these general types is called the coaxial resonator and is one in which coaxial conductors are used. They find their application largely as supports to the inner conductor of a coaxial line and are there referred to as stub supports. The second is the

rhumbatron or reentrant type, which has already been mentioned. The third, known as waveguide cavities, are ones in which the hollow volume may be thought of as a section of a waveguide which is closed off at both ends.

There are three general shapes of waveguide or nonreentrant cavities. They are spheres, cylinders, or rectangular prisms. The last two of these are easiest to understand because they may be thought of as pieces of cylindrical or rectangular waveguides closed off at both ends. The energy in such a piece of waveguide travels back and forth being sucessively reflected from each end. Resonance takes place if the time of travel is synchronized with the energy fed into the cavity.

V. SLUG TUNING OF RESONANT CAVITIES

Once a cavity is made to operate at a given frequency, it is often desirable to be able to vary this frequency over a small range without appreciably affecting the Q. This is accomplished by introducing a small metal screw or slug into the cavity.

If the slug is inserted so that it intercepts more H lines than E lines, the frequency will be raised; if more E than H lines are interrcepted, the resonant frequency will be lowered.[6]

The insertion of a metal slug into a resonant cavity so that it cuts more H lines than E lines is analogous to putting a

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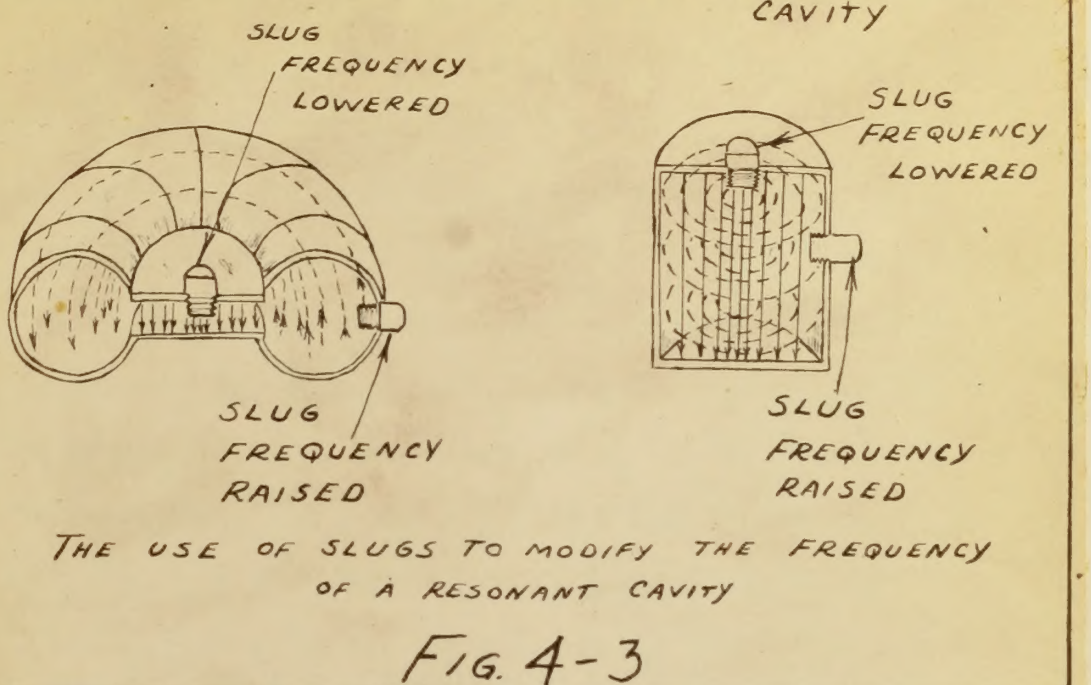
6. Ibid p 193



THE USE OF SLUGS TO MODIFY THE FREQUENCY OF A RESONANT CAVITY

FIG. 4-3

slug into a coil of wire which would lower the inductance and therefore raise the resonant frequency. If the slug was placed between the plates of a condenser so that it interrupted the electric field, it would raise the capacitance and therefore lower the resonant frequency.

VI. APPLICATIONS OF CAVITY RESONATORS

A list of some of the uses of cavities would include; frequency and wavelength measurement, microwave-frequency filtering, cavity-frequency conversion, antenna termination, coaxial supports, amplifier tuned circuits, transmitter receiver boxes, and frequency standards.[7]

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7. Ibid. p. 194

In the following sections of this chapter microwave generators will be considered but it is proper that some mention be made here of the type of oscillator operation that is used in connection with them. Cavities are used in conjunction with all three of the major kinds of generators. Disk-seal tubes and klystrons use the Rhumbatron type of cavity, while magnetrons usually use a modified form of cylindrical cavity with slot-coupling to the electron trajectories. This turns out to be the most logical procedure because the nature of a magnetron is such that no single electron beam is distinguished. However, in the klystron and the disk-seal tube all electrons follow essentially the same path and the resulting beam passes through the cavity.[8]

VII. MICROWAVE OSCILLATORS

When a signal is applied to the grid of an ordinary triode vacuum tube, that signal also appears on the plate with the same or increased power or voltage. However, if this signal is changing at the high rates of oscillation common to microwave frequencies, this situation does not prevail. There is a finite time of transit for the electron beam and this time must elapse before the grid voltage is felt by the plate. Usually the frequency is so low that this time of transit is negligible in comparison but at microwave frequencies the transit times may not be small compared to the period of modulation frequency. When

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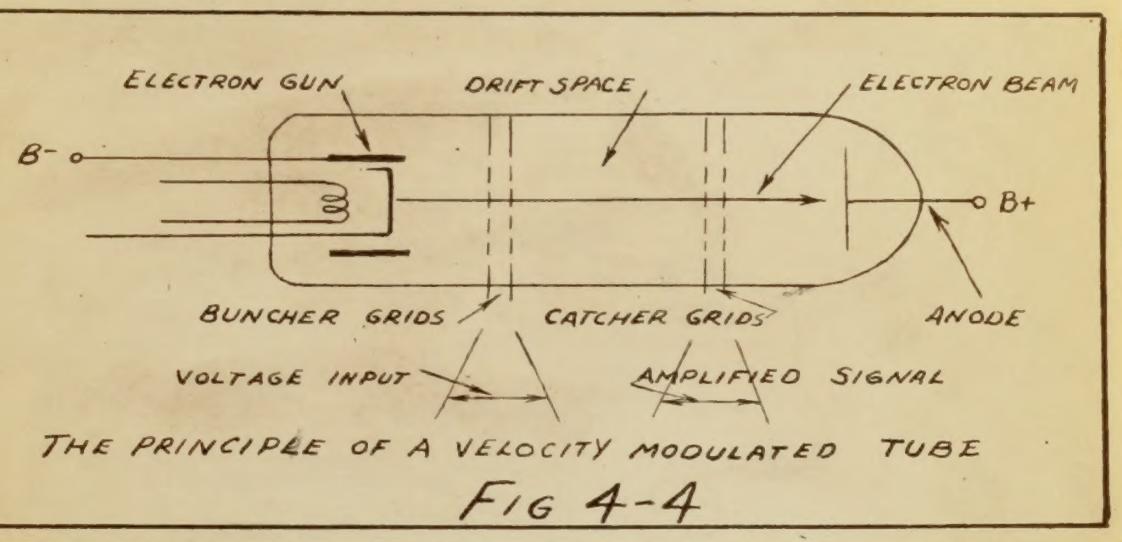
8. Ibid. p. 194

this situation exists, the tube is subjected to what is known as beam loading and the efficiency of the whole circuit is impared. For this reason, the usual type of amplitude-modulated tube is not useful at microwave frequencies.

VIII. THE KLYSTRON, A VELOCITY MODULATED TUBE

The problem of beam loading is solved by means of a velocity modulation tube. Such tubes have small transit times over very small distances between a pair of closely spaced grids. The average number of electrons remains constant and it is just their difference in velocity which is used to produce a signal.



THE PRINCIPLE OF A VELOCITY MODULATED TUBE

FIG 4-4

In a velocity modulated tube the conventional filament is replaced by a complete electron gun much the same as is used in a cathode-ray tube. The beam of electrons leave this gun and all proceed to the first buncher grid at the same velocity. They enter the buncher space without hesitation because the buncher

voltages are disconnected from the cathode. The voltage input is put across the first two buncher grids and when the second buncher grid is positive with respect to the first, the electrons between the two are accelerated, if it is negative, they are retarded.

If we start an observation at the time when the second buncher grid is negative with respect to the first, we see that the first electrons emitted will be moving at a relatively slow velocity. As that gird becomes positive with respect to the other, the electron velocity will increase until maximum electron velocity is reached. These later electrons are moving at a greater velocity than the earlier ones and if the drift space, which lies just beyond the buncher, is long enough, they will catch the slower ones.

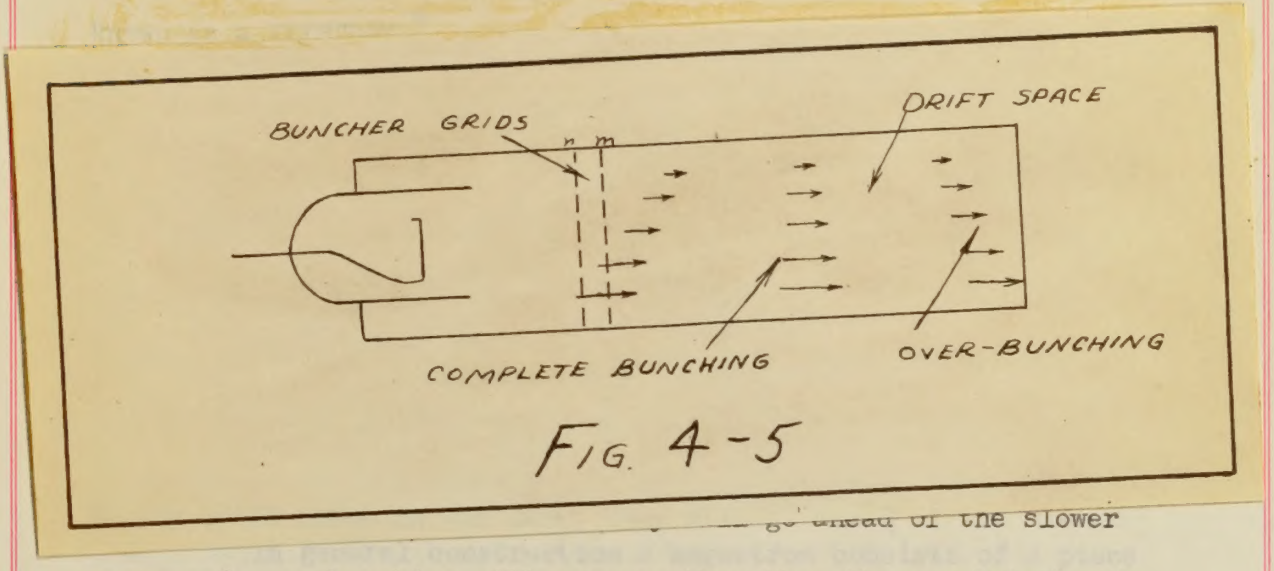


FIG. 4-5

ones and over bunching will occur rather than the complete bunching which is desired.

Another set of grids, known as catcher grids are used as a plate. Whenever a bunch of electrons pass through them the

voltage drops to zero. Thus, if the drift space is the proper length so that complete bunching occurs at the catcher grids, a voltage will appear between the catcher grids every cycle. Thus an alternating voltage appears at the cather grids in response to one on the buncher grids. There has been only one really successful method of applying or taking off the necessary ultra-high frequency alternating voltages that are needed in conjunction with buncher and catcher grids. It is accomplished by surrounding the grid pairs with a resonant cavity. Such a cavity is not limited by the stray capacity of ordinary tank circuits, and can be made to supply or receive a voltage at almost any desired frequency. A velocity-modulated tube of this type is known as a KLYSTRON.[9]

IX. MAGNETRON OSCILLATORS

While the subject of magnetrons or negative-resistance magnetrons (dynatrons) is much too extensive to be discussed in any detail in this paper, it is the opinion of the writer that some brief mention should be made of them because of their great importance and for the sake of completness.

In general construction a magnetron consists of a piece of straight wire which serves as a cathode surrounded by a cylindrical anode. The electric field between these two members tends

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9. Ibid p.227-8

to make the electron emitted by the cathode move in a straight line out towards the anode. However, a magnetic field is introduced to the system that tends to urge the electron sidewise as it moves out. If this field is strong enough, the emitted electron will never reach the anode (theoretically) but will simply travel in a circular path and end up back at the cathode. The return of these electrons to the cathode causes them to collide with electrons leaving the cathode and with positive ions which are attracted into the neighborhood of the cathode. Thus there exists a cloud of electrons around the cathode forming a virtual cathode which causes the actual cathode to act as if it had a diameter larger than its actual physical diameter. This and other factors causes (under practical conditions) some current to flow to the anode, and if any individual electron is traced over enough revolutions, it may be assumed to reach the anode ultimately.[10] Bombardment of the cathode also results in an increase in cathode temperature and precautions must be taken or adjustments made for this.

There are two general types of magnetrons. They are (1) the transit-time magnetron and the negative-resistance or dynatron type. The latter of these two is older and less useful than the former and it operates efficiently only at frequencies which are low in comparison to the transit time, and thus is relatively useless for microwave work. In general, they are only suitable for the generation of wave-lengths that are

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10. Ibid p. 241

longer than about 50 centimeters. Thus, for this discussion, we will confine ourselves to the transit-time magnetron. The general principals of both types are much the same.

As has been mentioned before, magnetrons are used in connection with resonant circuits or cavities. The magnetic field of the oscillator is adjusted into the neighborhood of its critical value and the frequency of oscillation is controlled not only by the resonant circuits but also by the strengths of the electric and magnetic fields. Because the electrons move through approximately circular orbits, it is now no longer necessary that the transit time be made small in terms of a cycle.

In the practical case, the cylindrical anode is not made up of one piece of metal but is composed of many (two or more) long, concave pieces which are insulated from each other. The resonant circuit in connection with the magnetron works with the flow of energy in the tube to make these different sections of the anode at different potentials with each other. As the electron is emitted from the cathode, it moves slowly out toward the anode and in an arc due to the force of the magnetic field. If this electron approaches an anode aector just as that part of the anode is being urged to become positively charged by virture of the resonant devices connected between it and the adjacent sectors, the electrons approach will help make the plate positive and in doing so it will tend to reduce the electrons orbit

and thereby cause it to head back towards the cathode. Such is the case at points 1,2, and 3, in Fig. 4-6. During these falls, the oscillation in the associated resonators is given a boost and the electron begins to spiral outward towards another anode and pick up more energy. Thus a rapid system of oscillation is set up in which transit time plays no part and it is merely the loops of the electrons approaching and receeding from the anode which takes the place of a grid and a plate in a conventional triode.

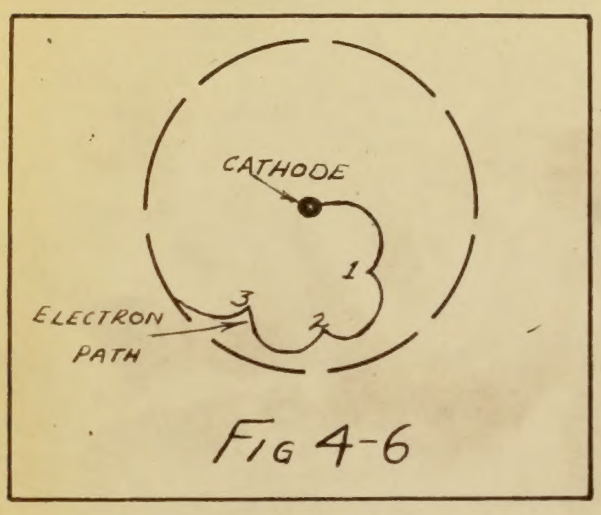
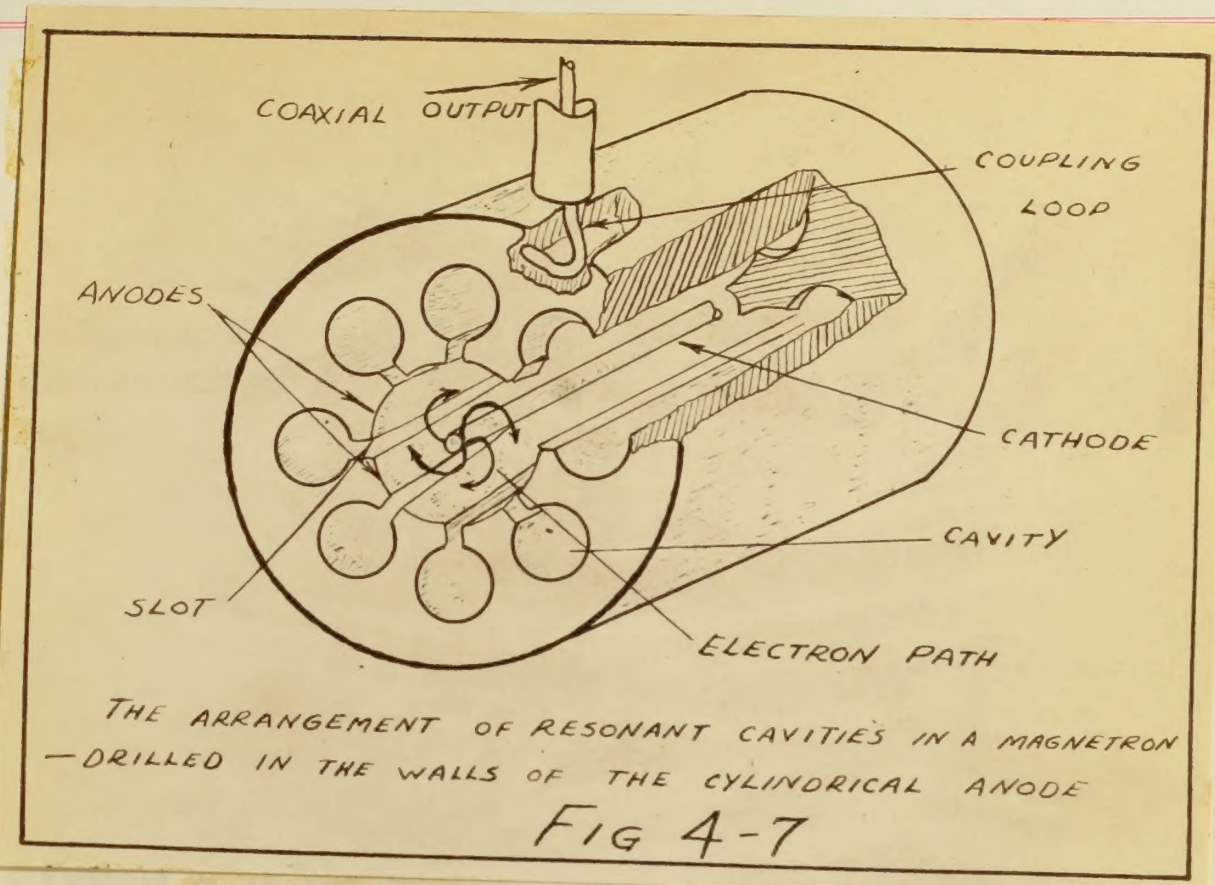


FIG 4-6

If the anode of a magnetron is composed of eight sections, eight resonant devices must be connected between the adjacent sectors. These act as lumped inductances connected across the capacitance existing between adjacent anode sections. These resonant devices are, in actual practice, resonant cavities and they allow a simple and rigid method or construction.



THE ARRANGEMENT OF RESONANT CAVITIES IN A MAGNETRON —DRILLED IN THE WALLS OF THE CYLINDRICAL ANODE

FIG 4-7

The useful load is extracted from a microwave magnetron by means of a coupling loop which is generally inserted into one of the resonant cavities. This loop need only be connected to one of the eight or more resonant cavities because, in a practical tube, all the resonant cavities are so closely coupled together that extracting energy from one is the same as taking it from them all.[11] The following quotation, while not a definition in any sense of the term, is a brief statement concerning magnetrons which may be used as a basis for summarizing thought about them.

"All magnetron vacuum tubes have some general features

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11. Ibid. p. 253

of construction in common. The anodes are always essentially cylindrical in shape, and the cathode always consists of a wire-like structure placed along the axis of that cylinder. Such tubes are used only as oscillators, and a resonant circuit is always used in conjunction with the anode. As with many other types of electronic oscillators, at low frequencies this resonant circuit may consist of a combination of lumped inductances and capacitance. At higher frequencies it may take the form of an open-wire transmission line, while at microwave frequencies it may consist of a single or multiple array of resonant cavities."[12]

X DISK-SEAL OR "LIGHTHOUSE" TUBES

Earlier in this chapter we saw that ordinary electron tubes were not satisfactory at microwave frequencies because the time of transit of an electron from the grid to the plate was too great and because shunt capacitances existed between the various elements of the tube which were detrimental to its functioning at ultra-high frequencies. There is, however, one type of triode vacuum tube generally known as the disk-seal type which has proven useful at frequencies extending up into the region of true micro-wave frequencies, ie: 3000 mc* and higher. Because of its general appearance, a disk-seal tube of this type is often referred to as a lighthouse tube.

The travel time of the electron from the cathode to the plate is greatly reduced in such a tube simply by mounting the cathode, grid, and plate very close together. "A typical disk-seal tube has a cathode-grid spacing of .004 inch and a grid-plate spacing of .012 inch. It is holding these dimensions to

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12. Ibid. p. 238

* Wavelengths of 10 cm., and shorter

good accuracy that makes the tube so sucessful."[13]

The unwanted inductance and capacitance values associated with electrode connections are reduced to a minimum by making the grid, plate, and cathode systems entirely separate from each other and attaching them together only through glass which forms the vacuum seal.

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13. Ibid p. 255

CHAPTER V

MICROWAVE RADIATION AND ANTENNA SYSTEMS

Up to now microwave radiation has been thought of only as a problem which affects the proper functioning of microwave oscillators and transmission systems. Yet it is this radiation which is the desired end-product and often the starting point of most microwave systems. Microwave generators produce the necessary high-frequency waves which are transported by waveguides or coaxial lines to some convenient radiating or antenna system. Here they are sent through the ether (to be conventional) to a microwave receiver either by reflection or direct transmission. So we see, in the overall view of microwave systems, that radiation or antenna systems play an important part.

1. ENERGY RADIATION AND POYNTING'S VECTOR

In free space or in any isotropic medium, the E and H vectors of electromagnetic waves are always perpendicular to each other. The magnitude and direction of energy propagation in the E and H system is given by a third vector called Poynting's vector. The numerical value of Poynting's vector varies with the cross product of E and H in the vicinity where the energy flow is to be

determined. Figure 5-1 gives an example of Poynting's vector and the calculations necessary to determine it. A slight investigation ofPoynting's vectors will help clarify the relationship between the E and H fields and their resultant radiation.

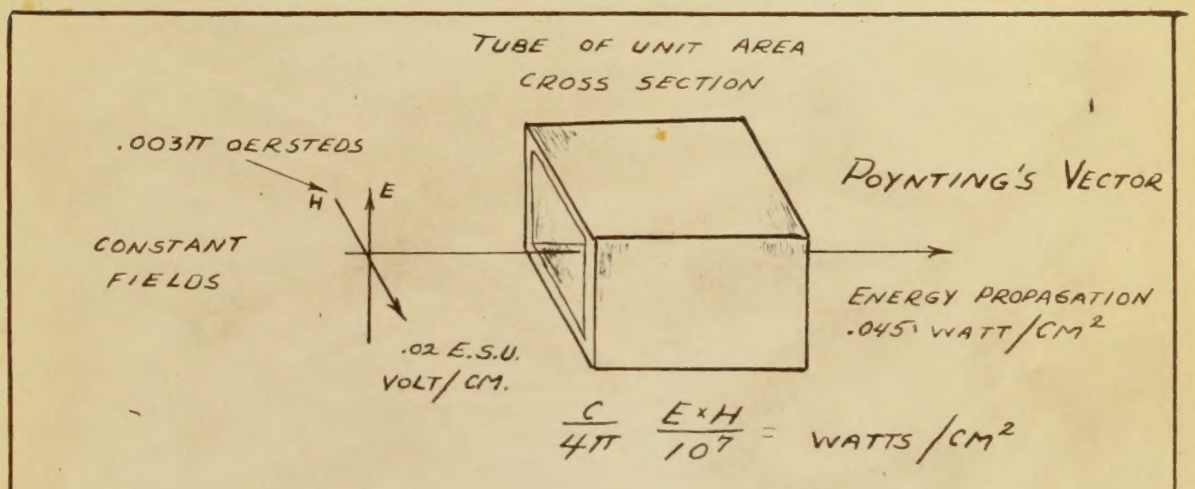

FIG. 5-1

When charges are accelerated the electric fields about them are much different than when they move at constant velocities. Let us assume that the charge Q (Fig. 5-2) is first observed at the point A and then moves a distance ∂x to B with an increasing velocity or acceleration. Then, after the charge reaches B it continues on a distance εx to D at a constant rate of speed because the accelerating force has been removed. Now let us

look at the nature of the field around the charge as it reaches D. If we consider T to be the time taken for the charge to move the entire distance AD, and the speed of light C to be the velocity of the field, the distance the

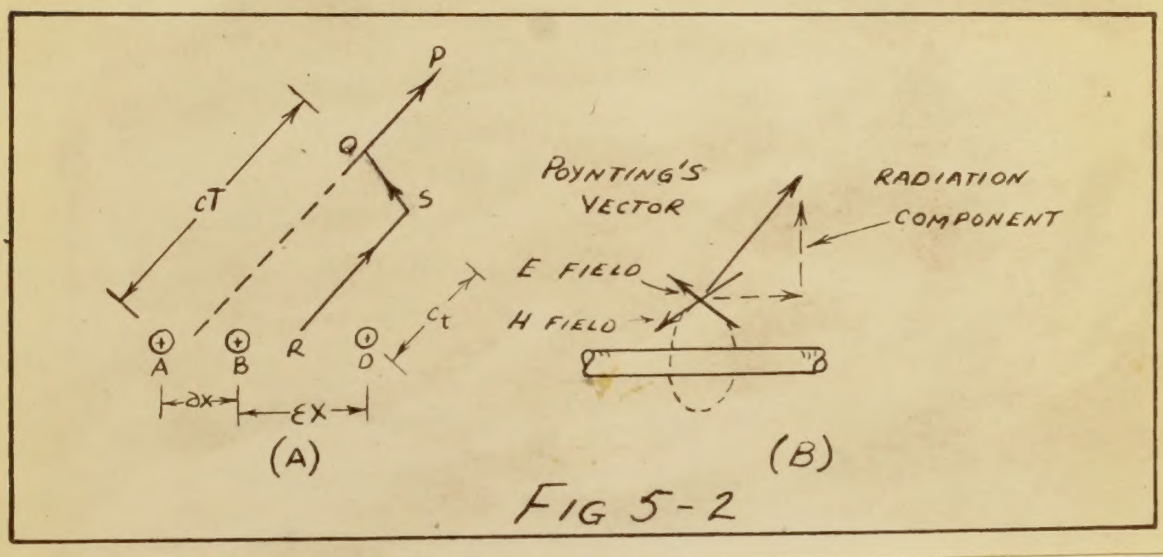

FIG 5-2

wave has traveled in the time T is CT. Thus, any point such as P, which is farther from the charge than CT, is unaffected by any of the motion until after the time of the final observation.

By the same reasoning, if t is the time the charge moves with constant velocity, the wave has only time to travel a distance Ct to point S at the time of final observation. Thus the line of force (Fig. 5-2 (A))must start out along RS and end up along OP. This line is surely continuous so S and O are connected and the portion SO shows the effect of acceleration.

In Fig 5-2 (B) the field arising from the acceleration of the charge (section SO) is drawn on a larger scale along with the magnetic lines of force and Poynting's vector. It is clear that the energy flow (represented by Poynting's vector) has a component outward from the path of the charge and it is this component that represents energy radiated out into space.

Thus we see that if the velocity of a charge is increased, energy is radiated. It makes no difference whether the charge is accelerated to the right or to the left or if the charge is oscillated back and forth as in an ordinary antenna, radiation occurs at regular intervals corresponding to each acceleration.

II. DIPOLE RADIATORS

Dipole radiators or half-wave dipoles, as they are usually called, are not dipoles in the usual sense of the term but are instead center-fed half-wave antennas which are connected to balance resonant lines. "A dipole is, strictly speaking, a pair of oscillating or stationary charges or magnetic poles, which are separated by a distance that is very small in comparison to a wavelength and which have opposite polarity."[14]

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14. Ibid p.211

Figure 5-3 shows a three-dimensional representation of a half-wave dipole antenna. Figure 5-3 (B) shows arrows radiating from the space between the two halves of the dipole which represents Poynting's vectors. It is clear from the figure that the actual radiation arises largely in the gap between the two halves of the dipole.

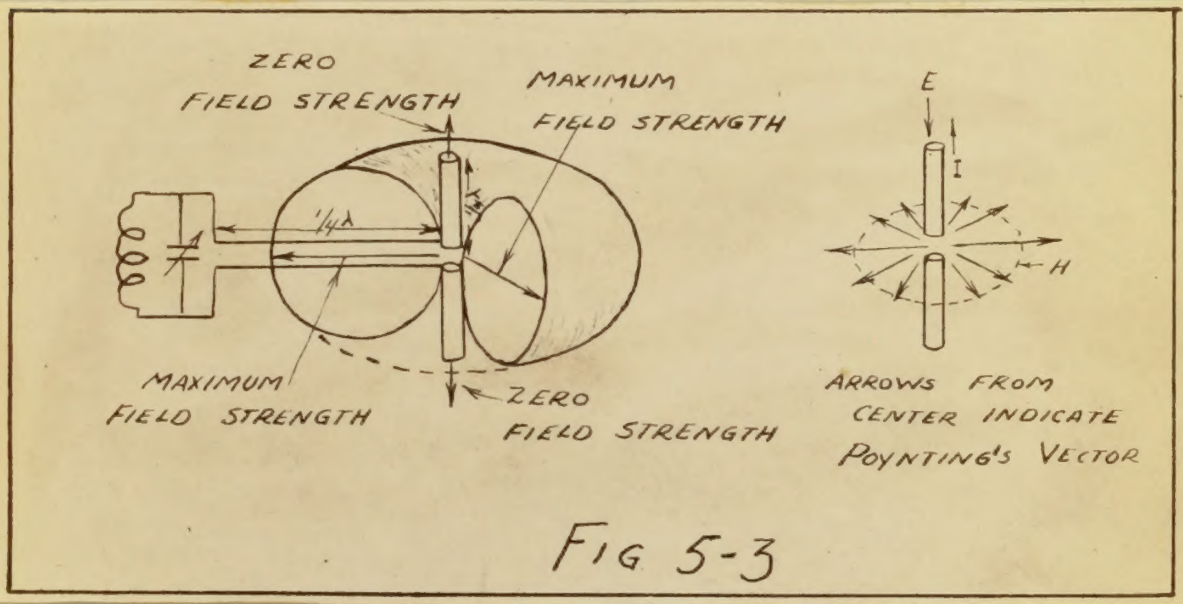

FIG 5-3

A further understanding of Fig. 5-3 will serve as a basis for understanding the action of the dipole as an energy radiator.

As the current flows out of the source (drawn here as a tuned circuit but probably a generator and a resonant cavity in actual practice) into the connecting wires, it travels in one direction until the polarity is changed and then it reverses its direction. Since this

flow in one direction is just $\frac{1}{2}$ wave-length, the charge has time to flow from the source to the end of one of the dipole radiators before it starts back. Since the polarity of the two terminals is opposite, the charge is moving away from the source in one half of the dipole while it is moving towards the source in the other. Thus the charge on the arms of the radiator acts as though it moved back and forth along the whole length. Any electromagnetic field set up by a current in one of the conductors (in a coaxial line) is just canceled by that in the other and thus radiation is obtained only from the dipole itself and not from the associated feed circuit.

As has been mentioned before, a dipole radiator is usually considered to be $\frac{1}{2}$ wave-length long. If this were actually true each half of the dipole would be $\frac{1}{4}$ wave-length. This is not actually the case. Certain correction factors must be introduced which make the radiator 10 to 20 percent shorter than the theoretical length. One correction is necessary because the electrical waves act as though the radiator was not connected at the physical junction to the feed but rather at some distance down the feed circuit. The usual design procedure is to make the arms of the dipole slightly too long and then trim them down until standing-wave-ratio measurements show that the antenna is accepting an

optimum amount of power.

Dipoles are frequently used as radiators in connection with waveguides as well as coaxial lines. When used in this manner they are parasitic in function in that they absorb energy from the wave guide and reradiate it. Figure 5-4 shows an example. The dipole is mounted on a small reflecting plate so that it faces the waveguide. The reflecting plate is connected to the waveguide by a low loss dielectric which allows the energy reradiated by the dipole to reach the reflector and form the radiated beam.

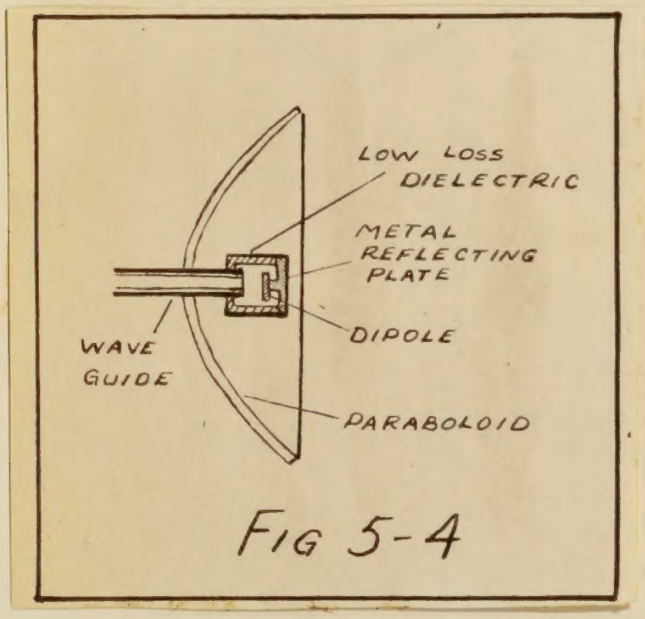

FIG 5-4

III. MICROWAVE FOCUSING

The size of microwaves makes it possible to build radiating systems that are large compared with the wave-length of the radiated energy. This is not true of conventional radio waves and only at frequencies as great

as those used in the microwave range is it practical to use specially constructed surfaces to focus the radio waves.[15]

The most common reflecting system used in connection with microwaves is the well known parabolic reflector. In general, the situation is analogous to that of light and the shape of the beam depends on the shape of the reflector and the position of the radiating source. However, it is not possible to transmit a microwave-radio beam which is exactly cylindrical in shape. In the microwave case it is not the exactness of manufacture of the parabolic surface of the reflector that is the limiting factor. Rather, it is diffraction of the waves around the edge of the reflector which prohibits transmission exactness. The larger the reflector in comparison with the wave-length, the closer the approach to the ideal of a cylindrically shaped beam. In general the narrowness of the radio beam is a function of the size of the dish only, if the placing of the feed and the shaping of the disk are correct or nearly so.[16]

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15. Ibid p.199
16. Ibid p. 203

IV. SPECIAL APPLICATIONS OF ANTENNAS

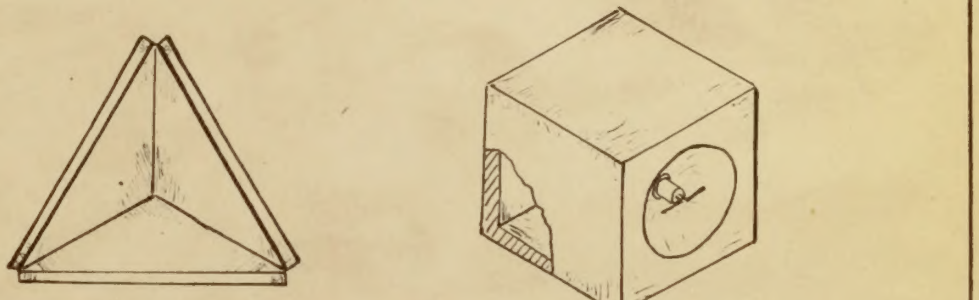
Certain situations have arisen in the practical application of microwaves, especially in radar, that have necessitated the development of special antenna arrays. One problem that was inherent in search radar systems was to produce a beam of relatively large angular crossection, such as 30 degrees or more, which had sharp beam edges so that a target could be accurately located by swinging the edge of the beam on and off of it. Such a beam was produced by placing a number of dipoles side by side so that their resulting beam was composed of a number of very sharp beams.

Frequently it was necessary that a radar produce a beam that was broad in one direction but narrowly restricted in the other. This may be accomplished by means of a specially designed reflector. Such a reflector may be produced by cutting a parabolic reflector roughly in thirds and using only the middle third with two flat parallel sides replacing the edges which were cut off.

Corner reflectors produce polarization just as a Nicol prism does in the optical field. These reflectors are made up of two frames made of wood or some dielectric which are placed at 90 degrees to each other. The dipole radiator is inserted approximately at the midpoint along

the junction of the two. Parallel strips of wire or some conductor are stretched across the frames so as to form a group of parallel conductors in planes which form a 90 degree corner.

A variation of the corner reflector is useful in testing radar systems. This type of corner reflector



A CORNER REFLECTOR (A)

AN ECHO BOX (B)

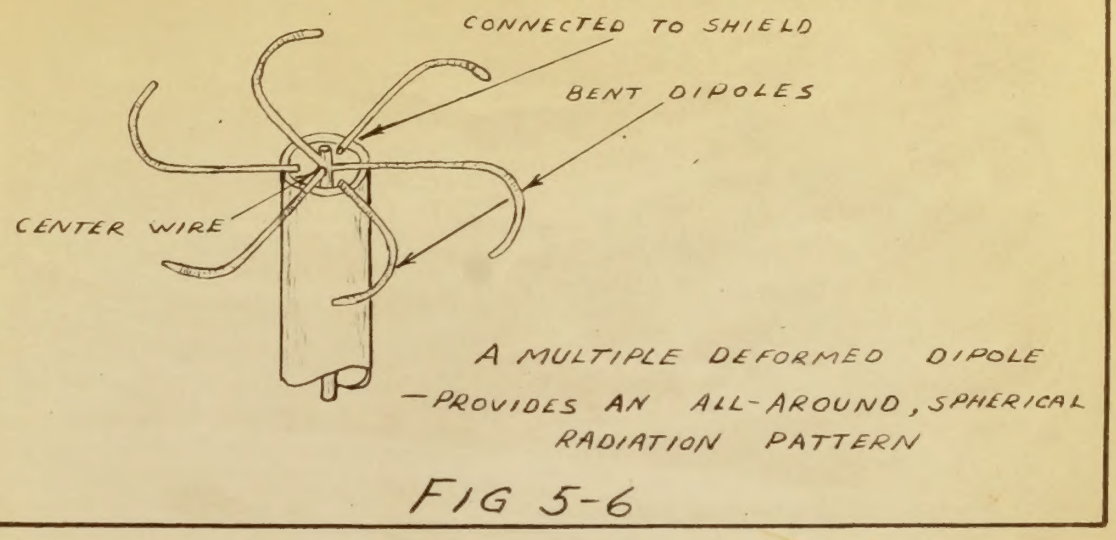
FIG 5-5

is made up of three planes of conducting materila put together to form a pyramid (see Fig. 5-5 (A)). This type of corner reflector is used without feeds of any sort as a simple and efficient source of echo signal. The addition of the third side removes any possibility of polarization.

Figure 5-5 (B) is a representation of what is called an echo-box. It is a hollow metal cube with a reflecting disk and a dipole antenna on one side. The

box acts as a resonant cavity and stores the energy which strikes the antenna. This energy is then retransmitted by the radiator at a somewhat longer period and at a reduced strength. The echo-box is also useful in radar tests because it sends back echoes of the transmitted pulse of energy so as to simulate distance measurements in terms of the time of flight of the radio energy.

Two major considerations for antennas for aircraft radar are that they must be designed to have no dead spots and must present a minimum of wind resistance. Dipole antennas present little wind resistance but there is a null in radiation at the end of the dipole. This null can be avoided by using a multiple deformed dipole such as is shown in Figure 5-6 which has a radiation pattern that is nearly spherical. The complete assembly of such an antenna is only about the size of a silver dollar.



A MULTIPLE DEFORMED DIPOLE —PROVIDES AN ALL-AROUND, SPHERICAL RADIATION PATTERN

FIG 5-6

V. ANTENNA GAIN

When a multiple dipole antenna is designed so as to radiate energy in all horizontal directions but not in unnecessary vertical coverage, this is known as antenna gain. Since the law of conservation of energy applies, the antenna does not manufacture energy but the so-called gain comes about simply because the energy is selectively transmitted in a certain direction at the expense of some other direction. If an antenna radiates equally in all directions its gain is said to be unity in all directions and such an antenna is called an isotropic radiator. If an antenna's radiation was all forward and none backward, the gain in all forward directions would be 2 and in all backward directions it would be zero.

VI. MICROWAVE PROPAGATION

As with radio waves, microwave propagation has to consider the fact that some of the radiated energy will strike the ground before it is received by the antenna. The situation with microwaves is not as important as in radio because radio's wider beam results in more earth reflection. In general, however, some of the energy reflects from the ground and is out of phase with the directly transmitted beam when it recrosses it. For this reason the antenna pattern depends not only on the antenna design but also on the height of the radiating antenna above the ground and on its angle of tilt with the ground.

CHAPTER VI

EXPERIMENTS IN MICROWAVE OPTICS

Since microwaves are the same as light waves except that they have a wave-length about one million times as great, we would expect that they would follow the laws that govern optical phenomena and produce the same effects such as interference, diffraction, and reflection which are common to light. The experiments that follow show that optical experiments with microwaves are possible with comparatively simple and inexpensive equipment. Furthermore, microwaves may be introductory to the study of x-rays and radio waves.

I. THE MICROWAVE TRANSMITTER

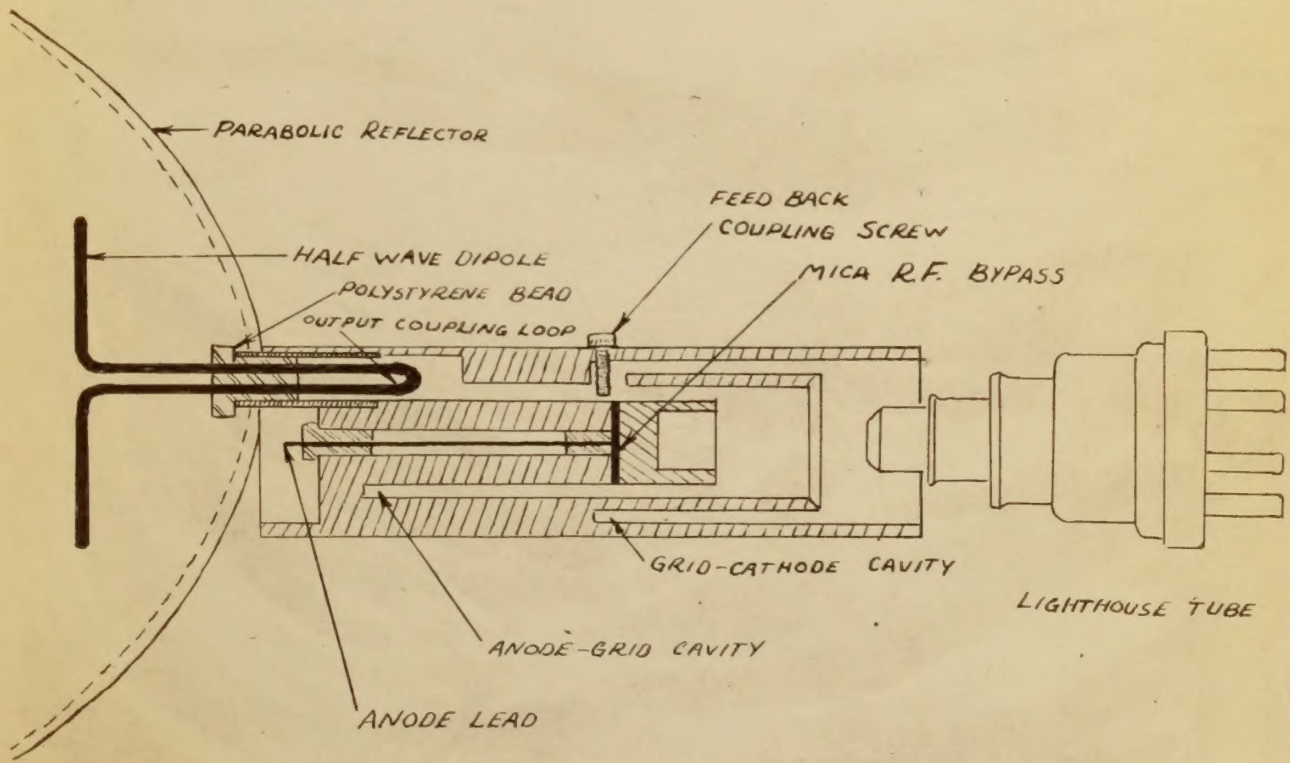
The laboratory microwave transmitter used to produce microwaves for the following experiments consisted of a power supply, an oscillator, and an antenna.

The power supply consisted of a 6.3 volt cathode heater, a 200 volt plate potential and a 10,000 ohm variable resistor which allowed the operator to vary the intensity of the radiated energy. An ordinary 110 volt 60 cycle alternating voltage was impressed on a transformer so that it could deliver the above stated voltages. The tube (see next paragraph) was self-rectifying.

The oscillator, which is the heart of a microwave transmitter, consisted of a resonant cavity and a "lighthouse" tube. The resonant cavity consisted of two coaxial resonant cavities with the disk seal tube as an intergral part of the outer one. The tube oscillated at a frequency of 3000 megacycles and the unit was a source of continuous microwaves apporximately 12 centimeters long.

The antenna system consisted of a dipole antenna and a parabolic reflector.

Figure 6-1 (below) is a cut-away diagram of the transmitter.



CAVITY OSCILLATOR WITH LIGHTHOUSE TUBE REMOVED

FIG 6-1

The oscillator or transmitter was plugged into the 120 volt, 60 cycle line and a short time allowed for the cathode of the tube to get hot. Then the knob on the back was turned to the right (variable resistor). The intensity meter was held about 10 feet away and observed. Then the feedback coupling screw (resonant cavity slug) was turned until the meter reading was a maximum. At this distance, the maximum reading should be about one-quarter of the full scale. If the reading was not this high, the antenna was moved in or out of the cavity. This adjustment, like that of the coupling screw, is critical. If the loop is too far out, the radiated power will be very low; if pushed too far in, the loading of the oscillator may be too great and oscillation will be prevented or unstable.

II. THE MICROWAVE RECEIVER OR INTENSITY METER

The intensity meter is show diagrammatically in Figure 6-2. The meter consists of a crystal detector with a half-wave dipole antenna and a short coaxial line. A layer of cellulose Scotch tape wrapped around the crystal holder acts as a by-pass for the radio frequency. The quarter-wave stub acts as a by-pass for the rectified current without reflecting the radio frequency at that point. Since the electric field undergoes a change of phase of 180 degrees upon reflection, the metal reflector

disc is placed $\frac{1}{4}$ wavelength behind the antenna so that the reflected wave will arrive at the antenna in phase with the incident wave.

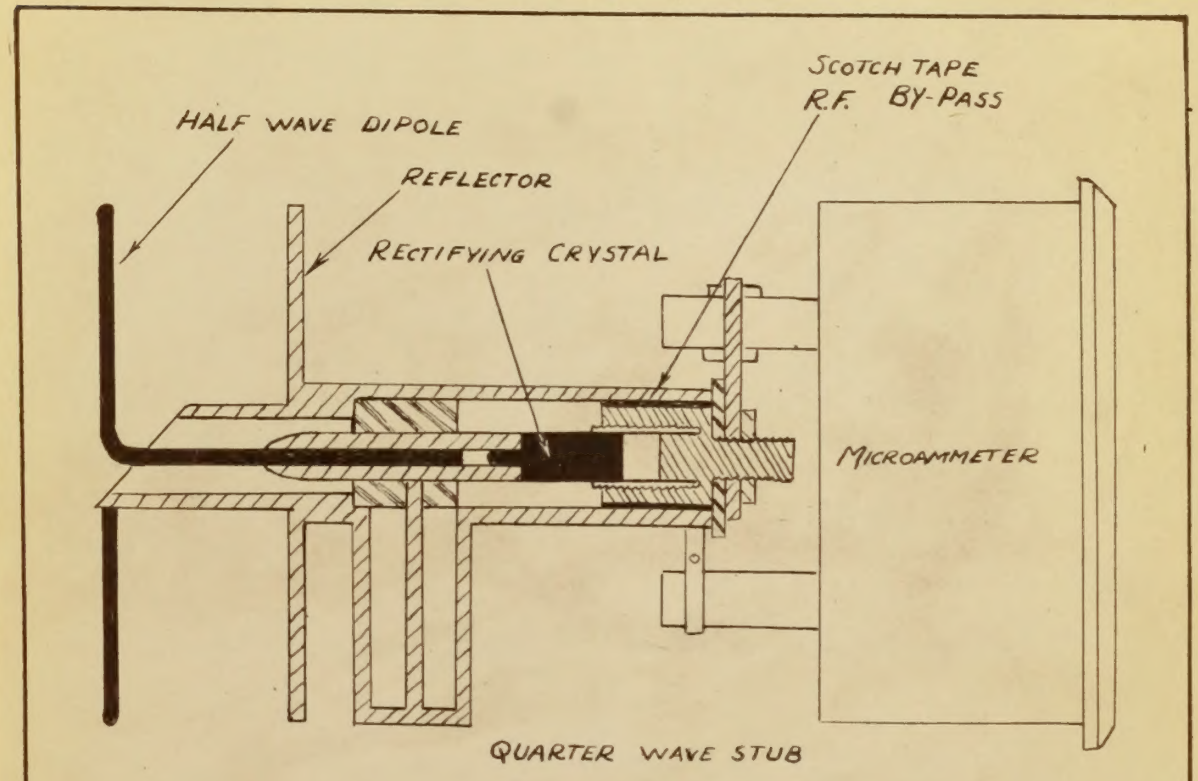


FIG 6-2

We know from optics, that the intensity is proportional to the square of the amplitude. In this receiver, the current through the crystal is very nearly proportional to the square of the potential across it. Thus the meter (G.E. Model DO-40 microammeter) reading is proportional to the intensity of radiation.

III. DETERMINATION OF WAVELENGTH

This experiment demonstrates standing waves and gives a fairly accurate measurement of the wavelength of the microwaves transmitted by the transmitter.

The intensity meter was moved back and forth

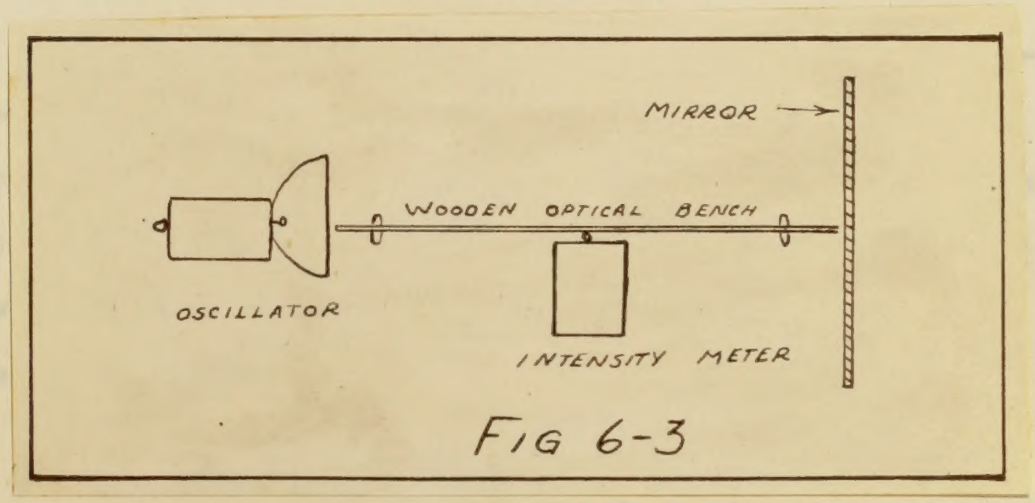
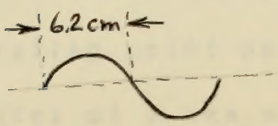


FIG 6-3

along the meter stick (see Fig. 6-3). The intensity decreased and increased as the receiver moved through points of maxima and minima. A meter stick---or wooden optical bench---was used instead of the regular metal optical bench because any iron in the field of the waves tends to distort the field.

The data of the experiment is given below.

Meter stick readings of minima:



81.4
75.4
69.1
62.8
56.6
50.6
44.5
37.9

Ave. difference =6.2 cm.

$\lambda = 2(6.2) = 12.4$ cm.

Thus we see that the wave-length of the micro-waves generated by the generator is about 12.4 cm. The length of the dipole antenna measures 5.9 cm. In length. This arresponds with the experimentally determined half-wave length of 6.2 cm. when the corrections noted in chapter V are considered.

IV. HUYGHENS' PRINCIPLE

When waves pass through an aperture they always spread out to some extent in a direction not directly exposed to the oncoming waves. This phenomenon is called diffraction and will be discussed in greater detail at a later point in this chapter. As an explanation for this diffraction, Huyghens*, nearly three hundred years ago proposed the theory or principle that bears his name.

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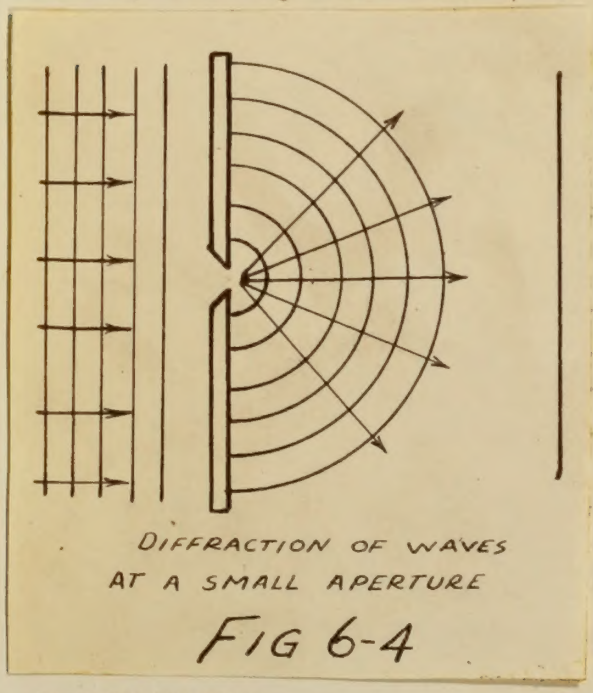
* The name is spelt both Huyghens and Huygens depending on the text. It is believed that Huygens is correct but for this paper both spellings will be used depending on the source from which the material was taken.

Huyghens' theory of light states that light is a wave motion disturbance in some medium, such as ether. Every vibrating point on the wave-front may be regarded as the center of a new wave. These new disturbances travel with equal velocity and they are enveloped by a surface whose properties are identical with the surface from which the secondary disturbances start. This new surface forms the new wave-front.[17]

When light falls on a small aperture it spreads out to some extent in all directions on the other side of the aperture rather than just appearing as a beam. Huyghens' principle explains this phenomenon of diffraction by stating that each point on the wave which traverses the aperture acts as a new radiating center and becomes the source of spherical waves. The total sum of all these waves result in a wave effect which acts as though a radiating source was located at the center of the aperture. (see Fig. 6-4)



DIFFRACTION OF WAVES AT A SMALL APERTURE

FIG 6-4

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17. HANDBOOK OF CHEMISTRY AND PHYSICS Thirtieth Edition p.2329

A very narrow slit placed in front of the microwave radiator will illustrate diffraction. A large piece of $\frac{1}{4}$ inch mesh wire with a narrow (abt. 4 cm.) slit cut in it was placed in front of the radiator and the microwave detector was moved about in front of the aperture. It was observed that the intensity of the radiation varied with the angle from a perpendicular bisector of the aperture towards the plane of the wire screen.

V. YOUNG'S PRINCIPLE OF SUPERPOSITION OR INTERFERENCE

When two beams of light cross each other, they do so without either one producing any modification of the other after it passes beyond the region of crossing. However, the amplitude and intensity of the beam (the resultant caused by the summation of the two beams crossing) in this region may be very different from the sum of those contributed by the two beams acting separately. "This modification os intensity obtained by the superposition of two or more beams of light we call interference (italics in the original). If the resultant intensity is zero or in general less than we expect from the separate intensities we have destructive interference, while if it is greater, we have constructive interference."[18] ~~Because of the~~

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18. Jenkins and White FUNDAMENTALS OF PHYSICAL OPTICS p.52

Because of the short wave length of light, this phenomenon was difficult to observe and was entirely overlooked in the time prior to 1800 when the corpuscular theory of light (advanced by Newton--against the wave theory advanced by Huyghens) was predominant. The first man to sucessfully establish the wave theory of light was Dr. Thomas Young an English physician and physicist. His work took a large step towards establishing the wave theory because he successfully demonstrated the interference of light--which cannot be successfully explained by the corpuscular theory, but which is easily understood by means of the wave theory.

When Huyghens' wavelets are produced at two points, an interference pattern is obtained in the radiant field. A brief discussion of the theory behind this would be instructive at this point.

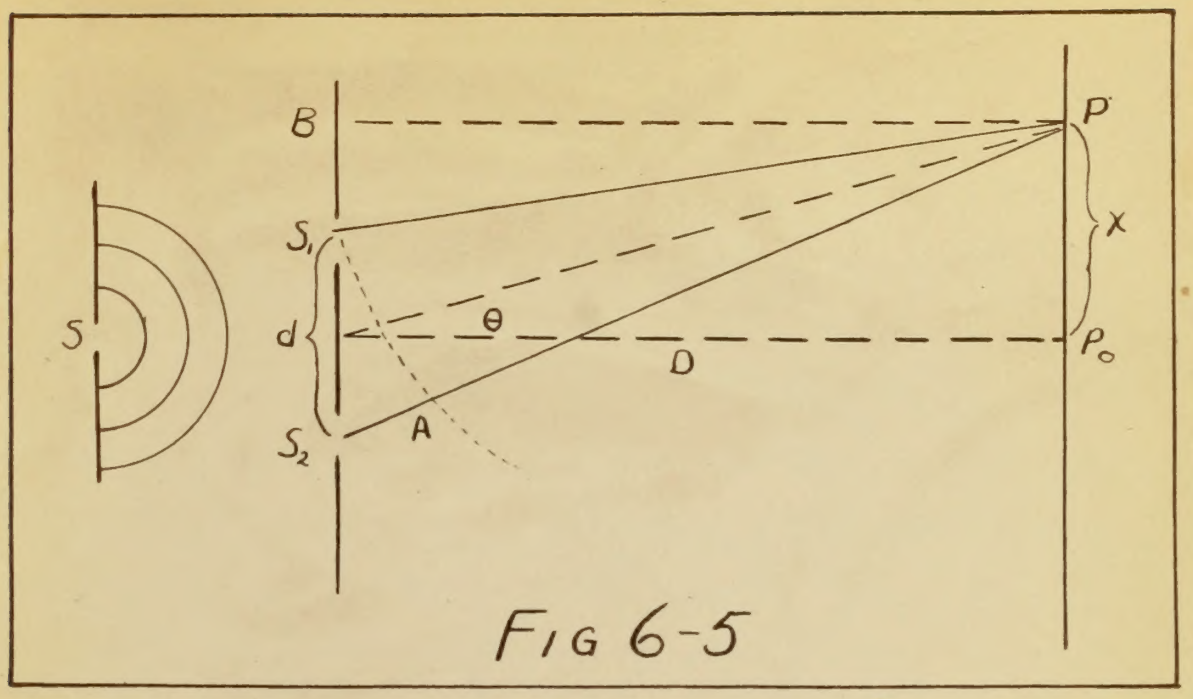

FIG 6-5

If, as is usually the case, the two slits S_1 and S_2 are the same size, the amplitudes r_1 and r_2 of the two waves x and y will be equal. Thus $r_1 = r_2 = r$. The Resultant intensity at any point P is

$$I = R^2 = 4r^2 \cos^2 \partial/2$$

where ∂ is the phase difference between the two superimposed vibrations and given by the relation

$$\partial = 2\pi/\lambda \times \text{path difference} = 2\pi/\lambda \ (S_2P - S_1P)$$

for the optical case:

BRIGHT FRINGES : $x = n\lambda D/d$

and

DARK FRINGES. $x = (n + \frac{1}{2})\lambda D/d$

where n is the order.[19]

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19. For a more complete discussion - see Ibid P. 57-59

The above two equations apply only when D is some thousand times larger than d or x and do not apply in the case of the usual microwave experiment.

The experiment that was conducted in the field of examination of the interference between directly transmitted beams of microwaves is not entirely analogous to the above optical case. Instead of using a single source and then interrupting the beam with a diaphragm which contained two apertures, a double source was obtained by means of an accessory to the transmitter (shown in Fig 6-6) which gave two secondary sources. The coupling loop was placed in the position of the regular dipole antenna and adjusted (in or out) to give maximum production of waves.

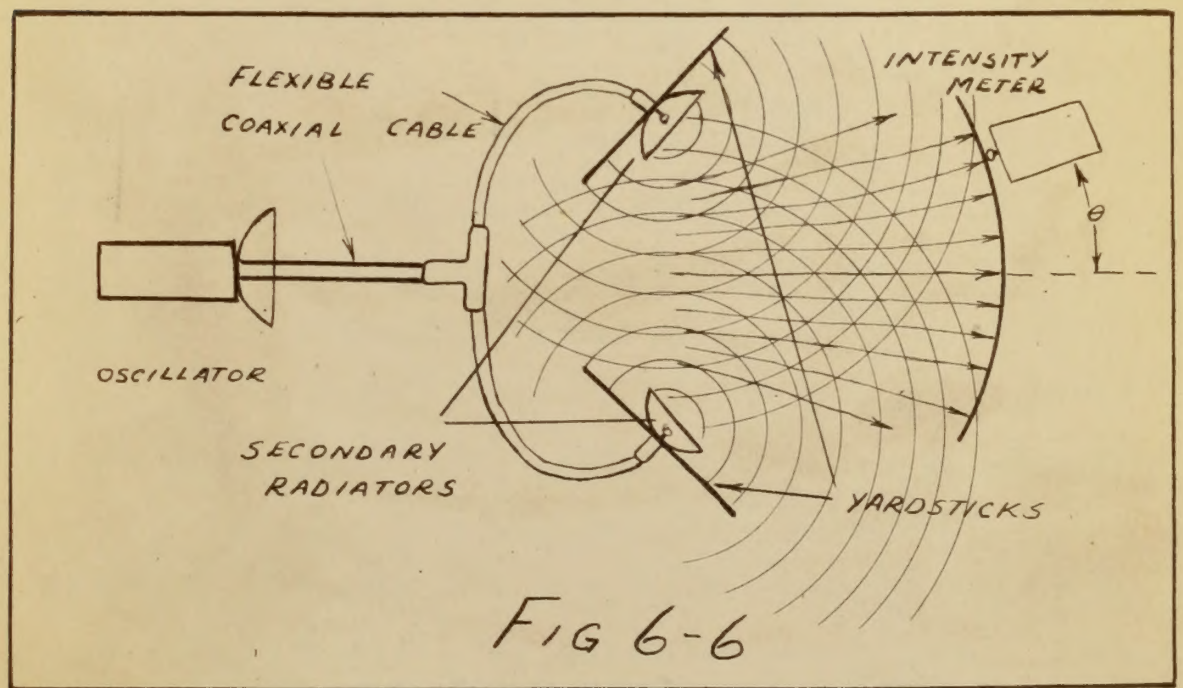
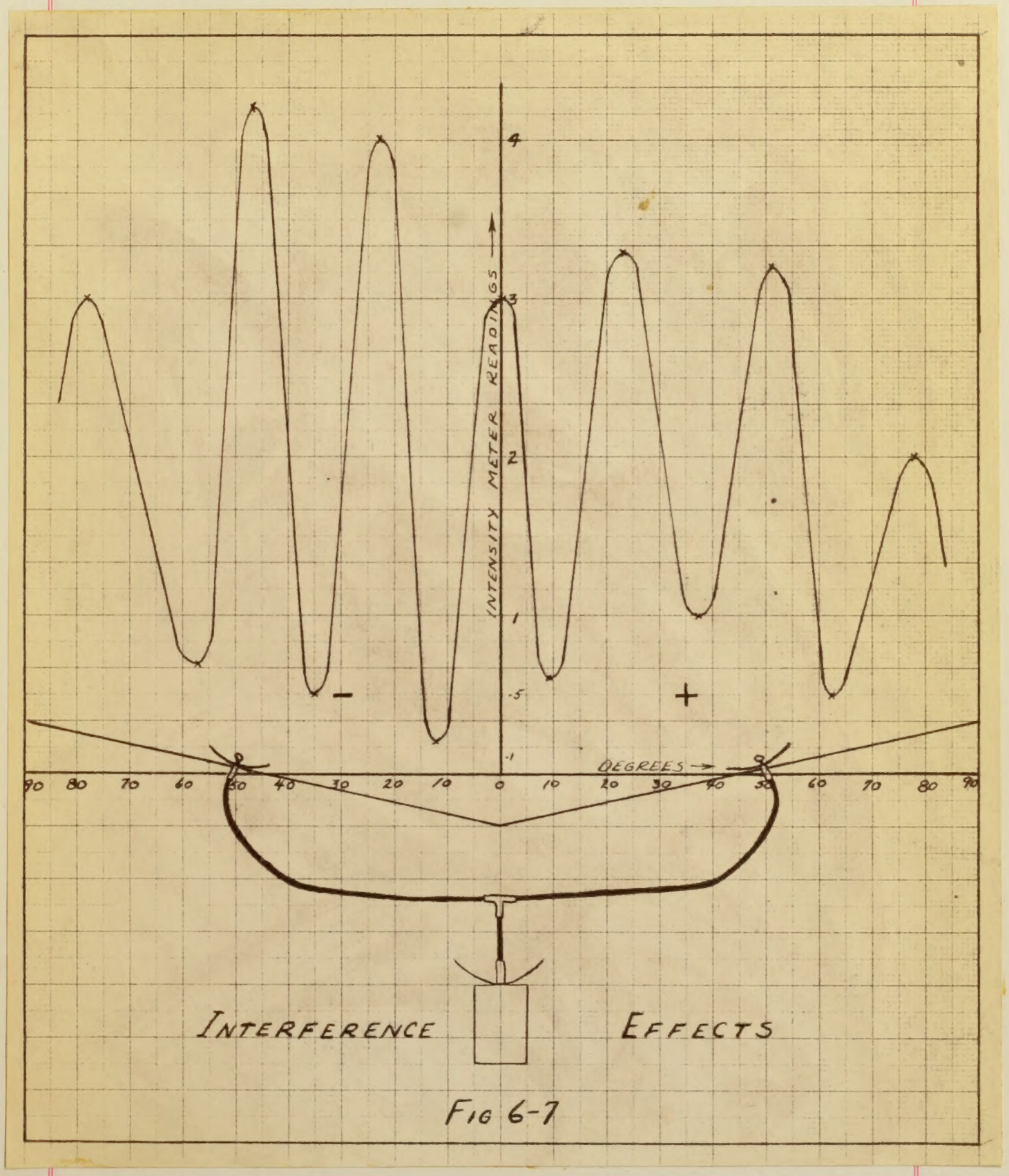


FIG 6-6

The two secondary radiators were mounted on two half-meter sticks and the intensity meter was moved about in front of them. Interference was observed and the results are shown graphically on page 71. The two half-meter sticks were placed at a slight angle to each other so that the beam of the radiators intersected each other. It was necessary to keep the reflectors behind the dipoles of the secondary radiators so that the antenna gain would be sufficient to give significant readings. However, with the reflector, the beams were so directional that unless the reflectors were placed at an angle to each other, the beams did not intersect except at such a distance that the intensity was too slight to be readable on the micro-ammeter receiver.

The successful use of the coaxial cable required the development of some experimental technique. Any sharp bends in the cable had to be avoided. The couplings which connected the various segments of the cable had to be securely fastened. The "T" coupling had to be maintained in as horizontal position as possible. When the secondary radiators were used with the microwave generator, the tuning slug had to be readjusted to give maximum radiation. The coupling loop of the coaxial cable should be pused into the dipole opening as fas as possible for maximum efficiency.

When maximum radiation is obtained from the two secondary radiators, the radiation of one of them is considerably less than the radiation from the generator when just the single dipole is used.



INTERFERENCE EFFECTS

FIG 6-7

VI. DIFFRACTION (FRESNEL TYPE)

When a beam of light passes through a narrow slit, it speeads out to a certain extent into the region of the geometrical shadow. This effect, already noted in part IV of this chapter, is one of the simplest examples of diffraction, ie: of the failure of light to travel in straight lines.

Diffraction phenomena are conveniently divided into two general classes: (1) Fraunhofer diffraction -- the source of light and the screen on which the pattern is observed are effectively at infinite distances from the aperture causing the diffraction, and (2) Fresnel diffraction -- where either the source or the screen, or both, are at finite distances from the aperture. Fraunhofer diffraction is much simpler to treat theoretically. It is easily observed in practice by rendering the light from a source parallel with a lens, and focusing it on a screen with another lens, placed behind the aperture, an arrangement which effectively removes the source and screen to infinity. In the observation of Fresnel diffraction, on the other hand, no lenses are necessary, but here the wave fronts are divergent instead of plane, and the theoretical treatment is consequently more complex.

The experimental work attempted with microwaves in diffraction was of the Fresnel type since both the source and the receiver were at finite distances from the aperture. (Finite in that the distances were not extremely large compared with the wave-length of the microwaves. The same distances in the optical case might be considered infinite compared with the wave-length of light.) Since the diffraction was of the Fresnel type, it will be the only type of diffraction considered here. However, for the sake of simplification, certain diagrams and equations that are to follow will be, correctly speaking, those typical of Fraunhofer diffraction. They, however, are assumed to be, in the broad sense, generally applicable to Fresnel diffraction.

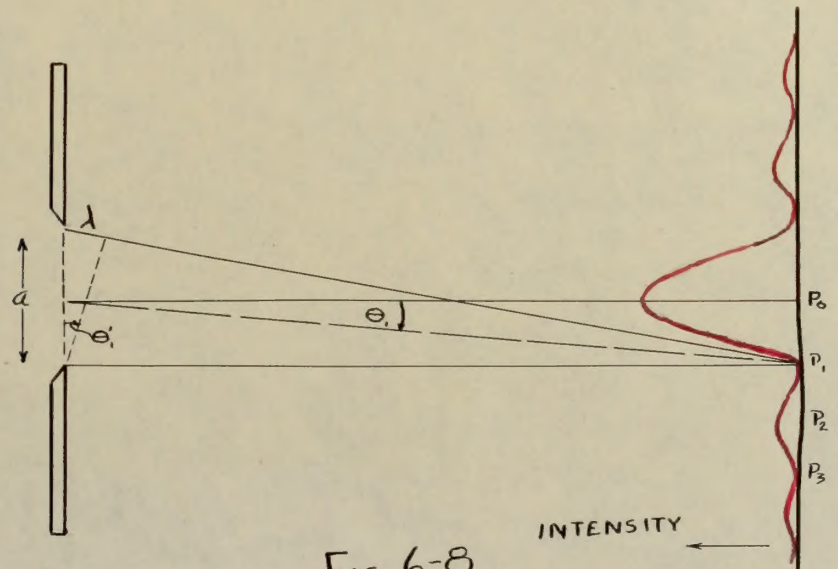


FIG 6-8

"A very clear idea of the origin of the single-slit pattern is obtained by the following simple treatment. Consider the light from the slit of the figure above coming to the point P_1 on the screen, this point being just one wave-length farther from the upper edge of the slit than from the lower. The secondary wavelet from the point in the slit adjacent to the upper edge will travel approximately $\lambda/2$ farther than that from the point at the center, and so the two will produce vibrations with a phase difference of π, and will give a resultant displacement of zero at P_1. Similarly the wavelet from the next point below the upper edge will cancel that from the point below the center, and we may continue this pairing off to include all points in the wave front, so that the resultant effect at P_1 is zero. At P_3 the path difference is 2λ, and if we divide the slit into four parts, the pairing of points again gives zero resultant, since the parts cancel in pairs. For the point P_2, on the other hand, the path difference is $3\pi/2$, and we may divide the slit into thirds, two of which will cancel, leaving one third to account for the intensity at this point. The resultant amplitude at P_2 is, of course, not even approximately one-third that at P_0 because the phases of the wavelets from the remaining third are not by any means equal.

The above method, though instructive, is not rigorous if the screen is at a finite distance from the slit. As the above figure is drawn, the shorter broken line is drawn to cut off equal distances on the rays to P_1. It will be seen from this that the path difference to P_1 between the light coming from the upper edge and that from the center is slightly greater than $\lambda/2$. Hence the resultant intensity will not be zero at P_1 and P_3, but it will be more nearly so the greater the distance between slit and screen, or the narrower the slit. This corresponds to the transition from Fresnel diffraction to Fraunhofer diffraction. Obviously, with the relative dimensions shown in the figure, the geometrical shadow of the slit would considerably widen with the central maximum as drawn. When the screen is at infinity, the realations become simpler, for then the two angles θ_1 and θ_1' in the figure become exactly equal (ie: the two dashed lines are perpendicular to each other), and $\lambda = a \sin \theta_1$ for the first minimum." [20]

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20. Ibid p.111-12

Since $\lambda = a \sin \theta_1$ for the first minimum,

$\lambda = a \sin \theta_n$ for any minimum, where n is 1 for the first minimum, 2 for the second, etc.

The discussion of amplitude in diffraction fringes is involved and not worthwhile in this paper. However, it should be mentioned that the intensities of the first, second, and third secondary maxima compared with the central maximum are 1/22.2, 1/61.8, and 1/121.

Thus we might assume that, when microwaves pass through a rectangular aperture which is wider than one-half wave-length, they would be diffracted in such a manner that there would be maxima and minima intensity at points for which the aperture contains respectively an odd or an even number of rectangular half-wave Fresnel zones. However the following information would lead us to modify to some extent the simplicity of this assumption.

"A diffraction problem is solved by adding together in proper phase and intensity, at a field point, the radiation from every point on the boundary that is responsible for the phenomenon; the applied mathematician achieves this result by finding a solution to the inhomogeneous wave equation which reduces at the aperture to the field which is in fact maintained there by the primary source. A solution to this problem due to Kirchhoff[2] has long served as the relation from which most optical diffraction formulae are derived..... The essential fallacy of the Kirchhoff solution is well known; Stratton and Chu[3] give a particularly clear discussion

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(2) J. A. Stratton, ELECTROMAGNETIC THEORY p.424

(3) J. A. Stratton and L.J. Chu, PHYSICAL REVIEW 56,99 (1939)

of the defects of the Kirchhoff solution which they offer in the same paper. Kirchhoff assumed that an electromagnetic field, incident from behind on a hole in a screen, maintainged in the whole its uninterrupted magnitude and polarization and was zero elsewhare; this assumption when applied to a metallic screen of good conductivity contradicts the field equations for, by it, electric lines are supposed to terminate discontinuously at the metal edge of the screen without the introduction of compensating effects. The solution due to Stratton and Chu permits the field to terminate in the same way but recognizes that the discontinuity can occur only if the electric lines terminate on alternating charge along the contour of the aperture; radiation from this alternating charge adds two contour intergrals to the surface integral which alone constitutes Kirchhoff's solution from the basis of the calculations which are discussed later."[21]

While experiments in slit diffraction do not appear practical using microwaves as a medium because of the relative difficulty of obtaining a parallel beam (for the Fraunhofer type) and because the low intensity of the source would prevent the removal of the reflector which causes a much too directional beam for the necessary size of such slits, the foregoing theory will serve as a useful introduction to the following section of this chapter.

VIII. DIFFRACTION PATTERN OF A CIRCULAR APERTURE

When a beam of light from a point source is interrupted by an opaque object, a shadow of that object will be cast on a viewing screen. The edges of this

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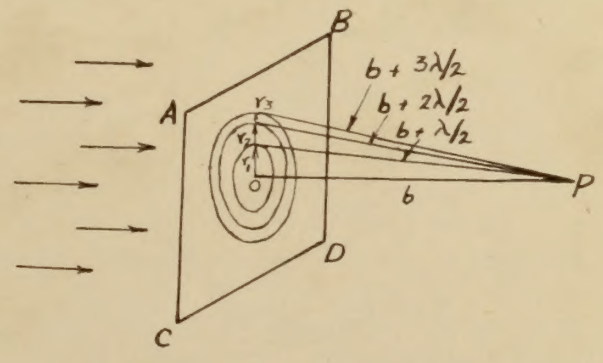
21. G. A. Woonton, D.R. Hay, and E.L. Vogan - JOURNAL OF APPLIED PHYSICS - Jan. 1949

shadow, however, are not absolutely sharp and, when examined closely, the shadows show a system of dark and light bands in the immediate neighborhood of the edge. Attempts were made by Newton and other advocates of the corpuscular theory of light to account for such small effects as due to the deflection of the light corpuscles in passing close to the edge of the obstacle. The correct explanation of this phenomenon, however, is found in terms of the wave theory of light in the brilliant work of Fresnel. His work in 1815 showed that, with the assumption that light is a wave motion, diffraction fringes could be accounted for to the most minute detail. An example of Fresnel's approach to diffraction problems follows.



THE CONSTRUCTION OF HALF-PERIOD ZONES FOR A PLANE WAVE

FIG 6-9

Let us first consider the effect which a plane wave will produce at a point ahead of the wave. Let ABCD in Figure 6-9 represent a place wave moving from left to right. Since every point on this wave may be considered as a source for secondary wavelets, let us consider the resultant effect of those wavelets on point P. In order to do this, we will first divide the wave front into zones in the following manner. Around the point O we describe a series of circles of radius r_1, r_2, r_3,..... r_n in such a way that each circle is $\frac{1}{2}$ wave-length further from P. That is, if OP = b, the circles will be at distances $b + \lambda/2$, $b + 2\lambda/2$, $b + 3\lambda/2$ .....$b + n\lambda/2$ from P. The areas of these zones may be computed by means of the Pythagorean theorem and we discover that their areas are equal and each equal to $\pi b \lambda$ except for a term λ^2 which may be neglected in the case of light (but not in the case of microwaves).

Actually there are three factors which determine the magnitudes of the amplitude of the light through these zones. (1) The size of the zones increases slightly because of the factor λ^2 (especially in microwave zones.) (2) Because the amplitude decreases inversely with the average distance of a zone, the magnitude of the terms are reduced by an amount which increases with n.

(3) Because of their obliquity, the amplitudes of outer zones should decrease. It may be shown that, in the case of light, the first factor above is just cancelled by the second. This leaves just the factor of increasing obliquity which tends to make the resultant amplitude of the wavelets from an outer zone less than those of an inner zone.

In general, however, if the hole has a radius of r equal to that of the first half-period zone, the intensity through that hole will be four times that due to the unscreened wave and the amplitude twice that of the unscreened wave.

"We conclude that the resultant amplitude at P due to n (italics in the original) is half the sum of the amplitudes contributed by the first and last zones. Allowing n to approach infinity, R_n becomes negligible, so that the amplitude due to the whole wave is just half that due to the first zone acting alone."[22]

In brief: Two adjacent half-period zones (half-wave zones or Fresnel half-wave zones) will produce essentially zero amplitude while two alternate half-period zones, or just one alone, will produce essentially twice the amplitude possible when no zones interrupt the beam.

In the case of light, these statements would only have to be modified to the extent that the further out from the center of the diaphragm the zone is, the

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22. Jenkins and White FUNDAMENTALS OF PHYSICAL OPTICS p.178

greater the obliguity of the waves and the less their amplitude. However, with microwaves, the λ^2 factor (which may be ignored when light is being used) is not insignificant and the size of the zones become larger with r.

Experimental work was done on the diffraction pattern of a circular aperture. Three easily removable circular half-wave zones were mounted on a wooden support and placed in front of the microwave generator. The intensity meter was mounted at a fixed distance behind the zones such as at a point P. Various arrangements of zones were tried and the resultant experimental intensities shown in Figure 6-10 on page 81.

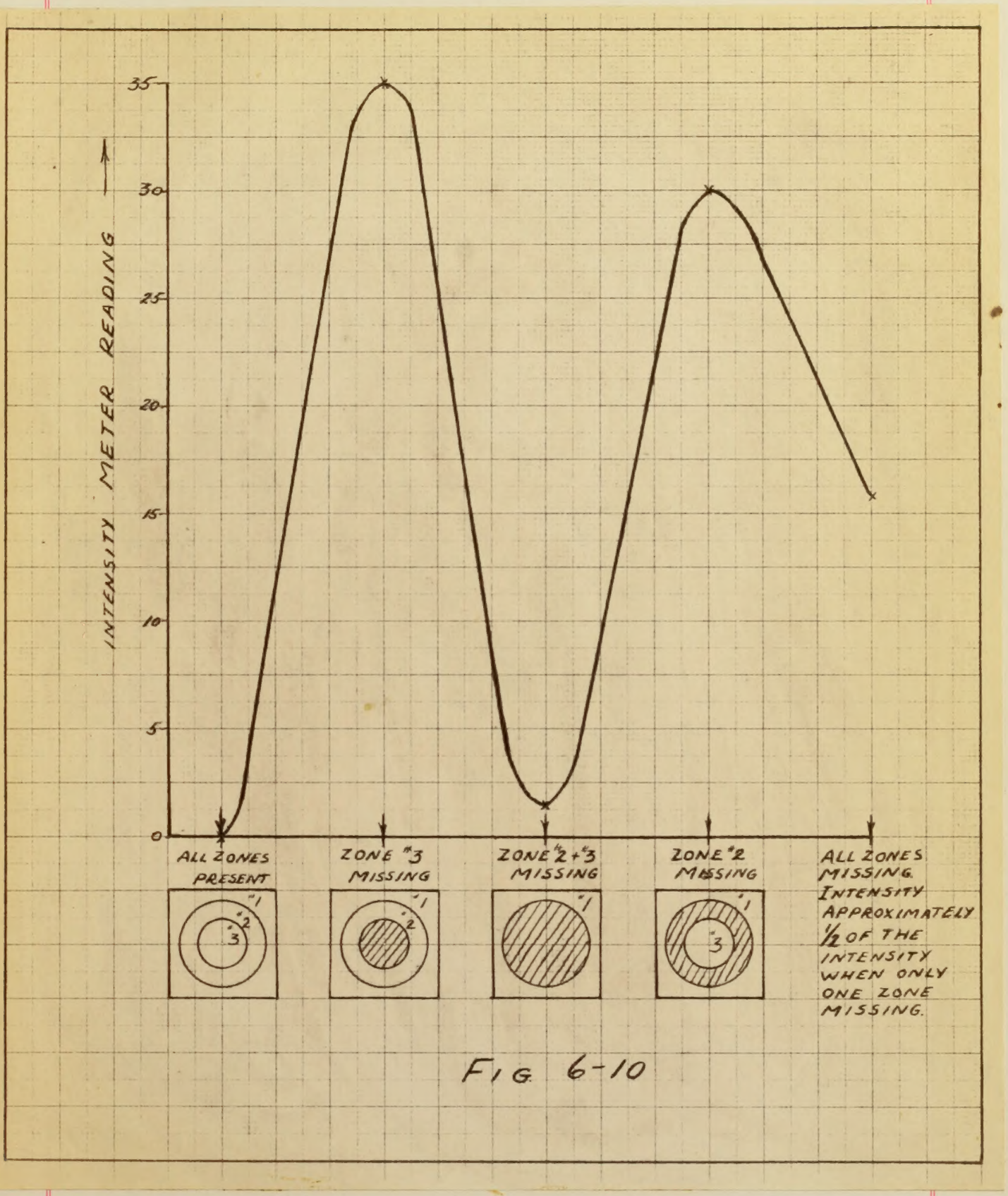

INTENSITY METER READING
35
30
25
20
15
10
5
0
ALL ZONES PRESENT
ZONE #3 MISSING
ZONE #2+#3 MISSING
ZONE #2 MISSING
ALL ZONES MISSING. INTENSITY APPROXIMATELY 1/2 OF THE INTENSITY WHEN ONLY ONE ZONE MISSING.
#1
#2
#3

FIG 6-10

VIII. INTERFERENCE EFFECTS

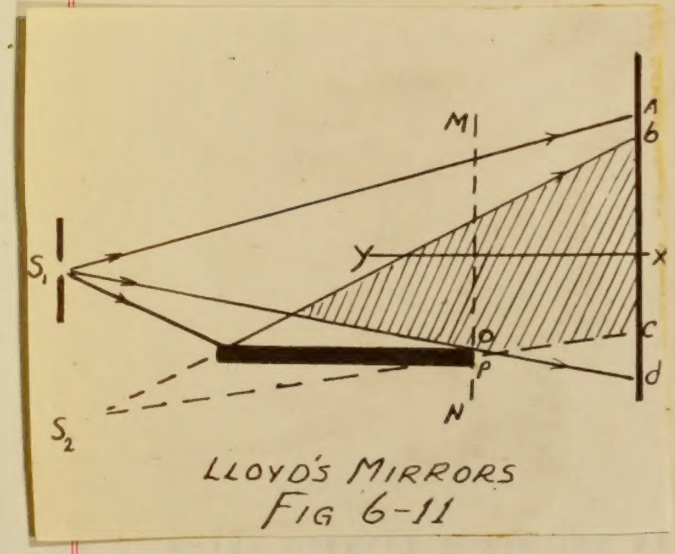
When two trains of waves of the same frequency move in the same direction but in the opposite sense, stationary waves are produced by interference. However, these stationary waves or interference fringes cannot be obtained from two separate sources such as two lamp filaments (in the optical case) set side by side because any train of waves from a filament is not continuous but changes phase suddenly in very short intervals of time (in the order of 10^{-8} sec.). Thus any interference fringes that might be set up by two separate sources would shift their position each time there is a phase change and no fringes would be seen. Any optical experiment that would show interference between two beams of light must utilize two sources which have a point-to-point correspondence of phase which can only be obtained by deriving the two secondary sources from one source. When this is done, any change of phase in the primary source will cause a change of phase in both of the secondary sources simultaneously and the difference in phase between any pair of points in the two sources will always remain constant and the interference fringes will remain stationary. "It is a characteristic of any inter-

ference experiment with light that the sources must have this point-to-point phase relation, and sources that have this relation are called choerent sources (italics in original)."[23]

IX. LLOYD'S MIRRORS

Lloyd's mirror experiment is especially important in any treatment of optical effects because, besides showing the interference of light from two coherent beams, it shows the change of phase of the light as it is reflected at grazing incidence from the reflecting surface.

As can be seen from Fig. 6-11, the waves from the sources S_1 are incident at a grazing angle on the reflector. A wave is reflected in such a manner that its arrival at the plane ~~a-b~~ is essentially the same as though it started from the virtual source S_2. In addition to the reflected wave arriving at the plane, there is also a wave coming directly from the source S_1 without reflection. In the



LLOYD'S MIRRORS
FIG 6-11

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23. Ibid p.66

region of overlapping of these two beams interference occurs, and can be observed (in the case of microwaves) by moving the intensity meter along a path from x to y.

As mentioned above, an important feature of Lloyd's mirror experiment lies in the fact that when a plate is placed in contact with the end of the mirror (position MN), the edge of the reflecting surface comes at the center of a dark fringe (we are considering the optical case), instead of a place of bright fringes as might be expected. This means that one of the two beams of light has undergone a phase change of π . Since the direct~~ion~~ beam could not change phase, this experimental observation is interpreted to mean that the reflected light has changed phase at reflection. "It is a matter of experimental observation that in the reflection of light....., the phase change of π occurs when the light strikes the boundary from the side of higher velocity."[24]

The above discussion of change of phase of the reflected beam is, as noted, for the optical case. It has, however been observed to be true for microwaves.

The results obtained from this experiment were recorded and are shown in Figure 6-12. The graph (Fig. 6-12) clearly shows the existance of interference fringes.

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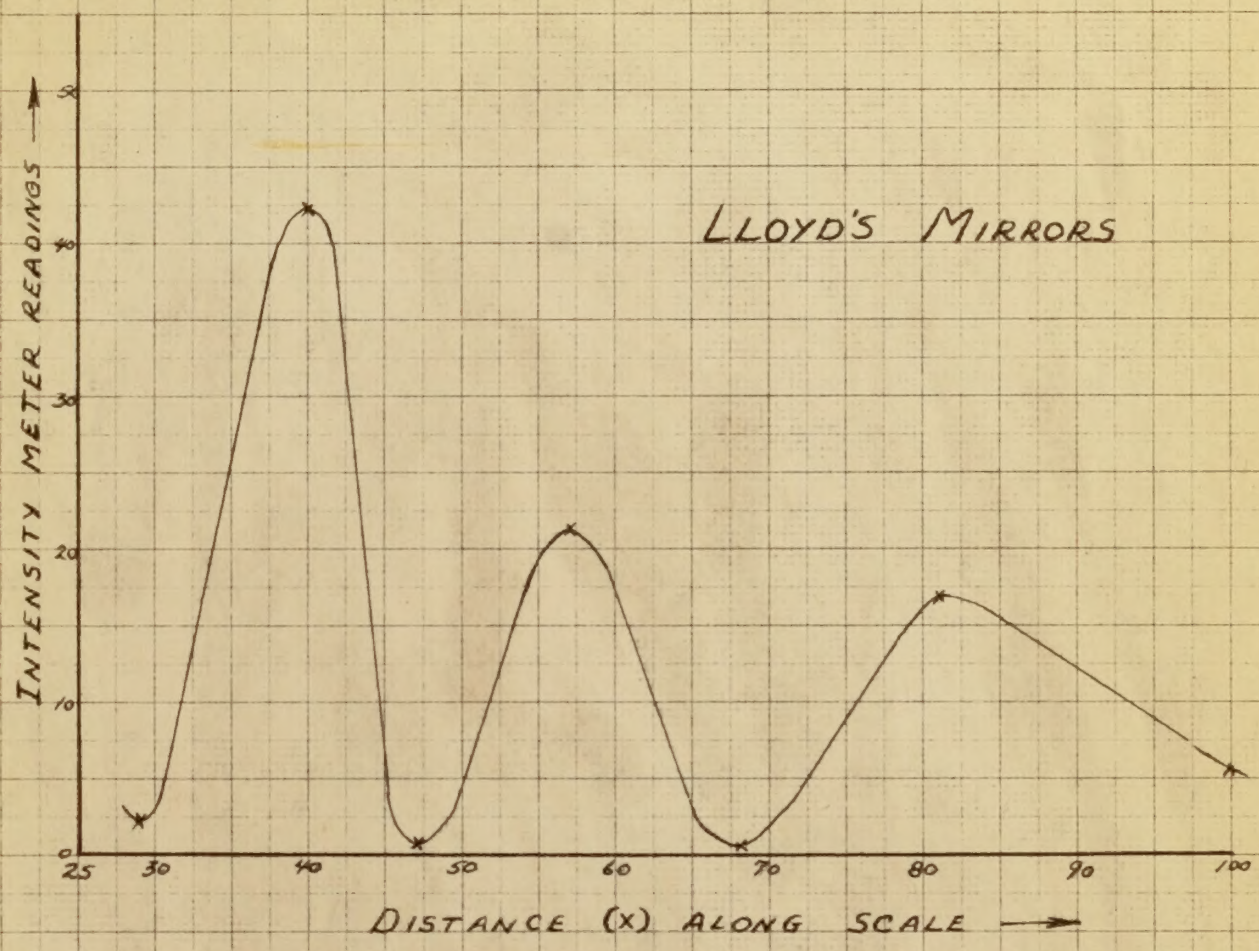
24. Ibid p.25


LLOYD'S MIRRORS
INTENSITY METER READINGS →
0
10
20
25 30 40 50 60 70 80 90 100
DISTANCE (x) ALONG SCALE →

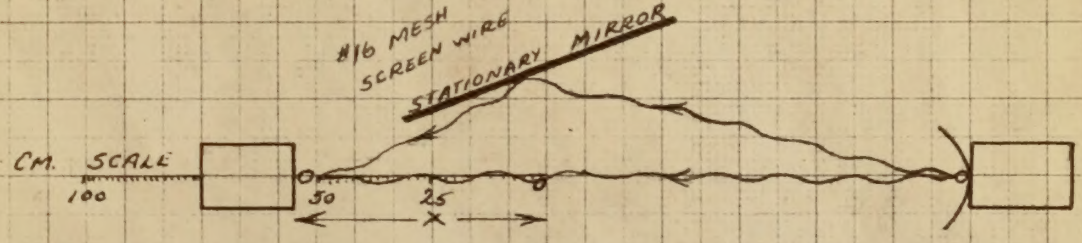
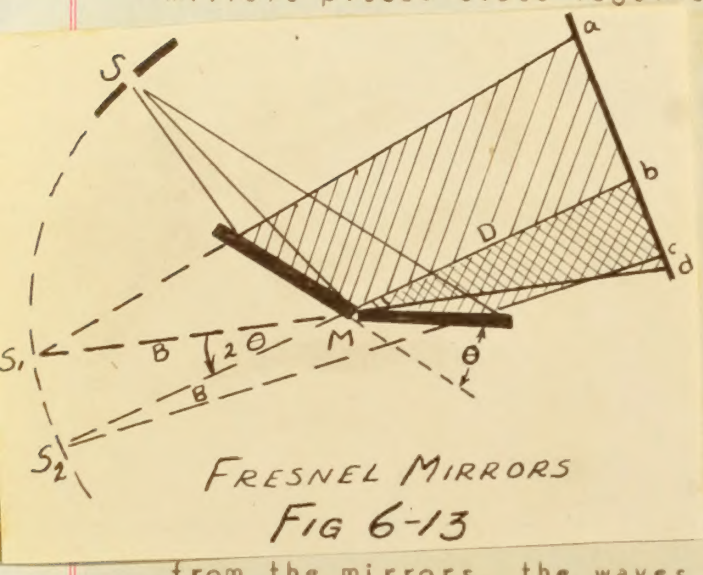

#16 MESH SCREEN WIRE
STATIONARY MIRROR
CM. SCALE
100
50
25

FIG 6-12

X. FRESNEL MIRRORS

As shown in figure 6-13, the waves from a source S are split into two beams by reflection from two mirrors placed close together so that their planes make a small angle θ with each other. On that part of the screen where the two beams overlap, interference fringes are obtained. The explanation of these fringes is similar to that for Lloyd's mirror case. After reflection from the mirrors, the waves arriving at the sereen (da) appear to come from virtual sources S_1 and S_2. The relations between fringe separation and the geometry of the figure are such that if we call d the distance between the virtual sources, D the distance Mb, and λ the wave-length, the distance x between fringes on the screen will be related to these quantities by



FRESNEL MIRRORS
FIG 6-13

$$\lambda = xd/B+D$$

The interval d can be calculated from the fact that d = 2Bθ (θ now being the angle between the mirrors).

The graph (Fig 6-14) shows good qualitative results of the production of interference fringes using microwaves.

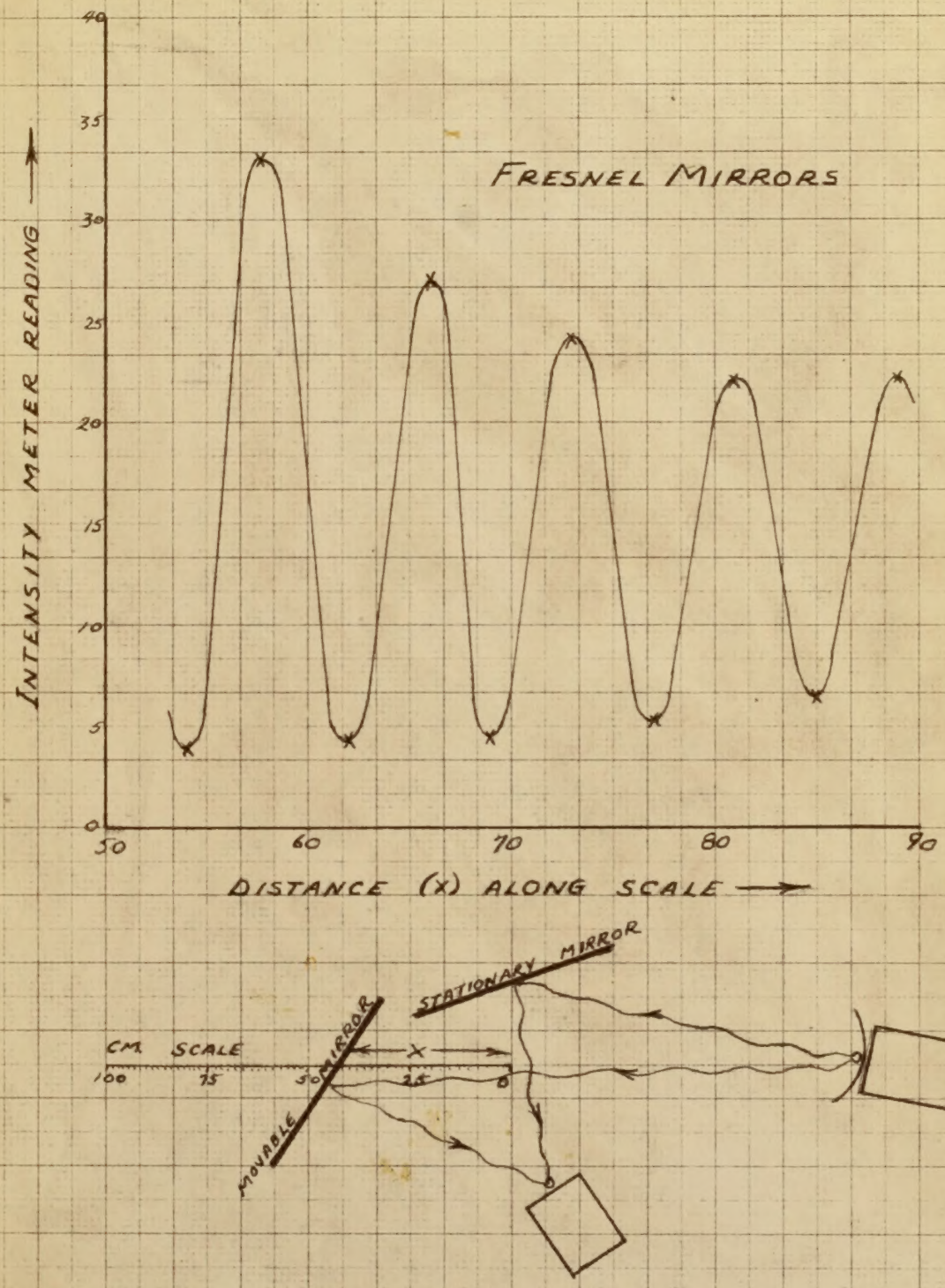

FRESNEL MIRRORS
INTENSITY METER READING
0
5
10
15
20
25
30
35
40
50
60
70
80
90
DISTANCE (X) ALONG SCALE
STATIONARY MIRROR
MOVABLE MIRROR
CM SCALE
100
75
50
25
0
X

FIG 6-14

XI. THIN FILMS

If a partial reflector interrupts a beam of light or microwaves, part of the beam will be reflected and part transmitted. If the transmitted part of the beam is reflected by a mirror in a direction that will cause it to intersect the beam reflected by the partial reflector, interference effects can be noted.

The apparatus was set-up as shown in Figure 6-15 and reflector b was moved along a scaled path so that it remained as nearly parallel to a as possible. Interference also is obtained when b and a are not parallel to each other as long as the beam transmitted by a and reflected by b impinges upon the intensity meter. When the reflectors are not parrallel, the set-up illustrates reflection by two surfaces of a wedge.

A partial reflector may be substituted for b. The set-up then illustrates the use of a thin film bounded by two transparent surfaces, whereas the arrangement shown in the figure illustrates the situation when one of the surfaces is opaque.

The results obtained, shown in Figure 6-15, give a good graph of interference fringes.

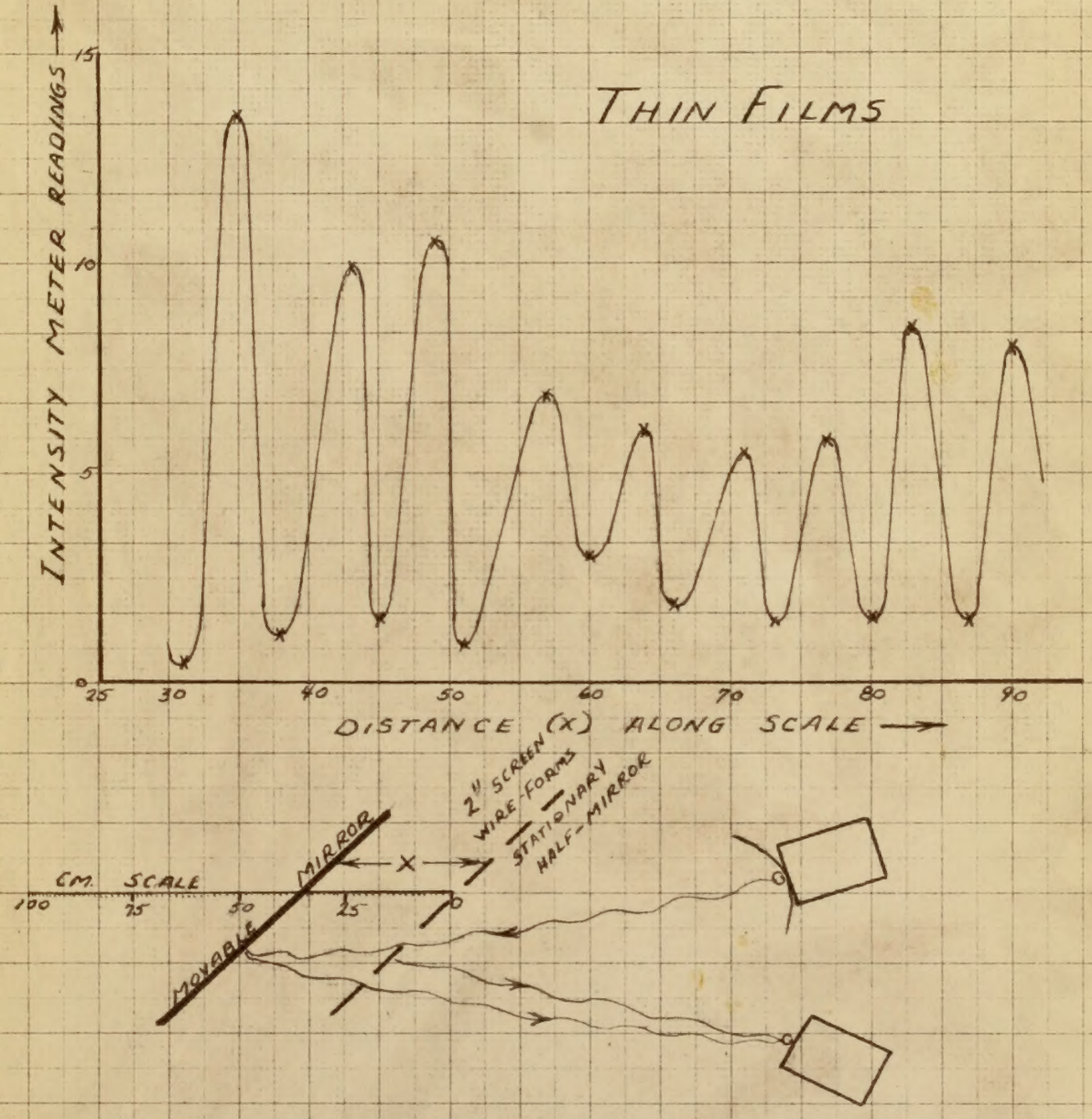

THIN FILMS
INTENSITY METER READINGS
15
10
5
0
25
30
40
50
60
70
80
90
DISTANCE (X) ALONG SCALE
2" SCREEN
WIRE-FORMS
STATIONARY
HALF-MIRROR
MIRROR
X
CM. SCALE
100
75
50
25
0
MOVABLE

FIG 6-15

XII. FABRY-PEROT INTERFEROMETER

The situation that exists in a Fabry-Perot interferometer is similar to the set-up used for the preceding experiment. The apparatus was set-up (as shown in Figure 6-16) with two semi-(or partial) reflectors in the way of the transmitted beam and with the microwave intensity meter behind both of them. The microwaves, after leaving the transmitter, are transmitted by the first semi-reflector (a) and then are broken into two parts by the second semi-reflector (b). One part of the original train continues on to the intensity meter. The other part is reflected back from (b) to (a) and then reflected back to (b) again. Some of these "double reflected " waves continue on through (b) to the meter, the remaining waves return to (a) again, etc. Thus, two groups of waves are transmitted by (b) to the meter. Interference takes place at the meter. This interference is constructive or destructive depending on whether the path difference between the two paths is some multiple of even $\frac{1}{2}$ wave-lengths (constructive) or some multiple of odd $\frac{1}{2}$ wave-lengths (destructive).

The apparatus was set-up as shown in Figure 6-16. Semi-reflector (b) was moved. (Either mirror could have been moved).

The optical equation for the Michelson interferometer holds true in this case. From this the wave-length of the microwaves can be determined.

$$2nd = n\lambda$$

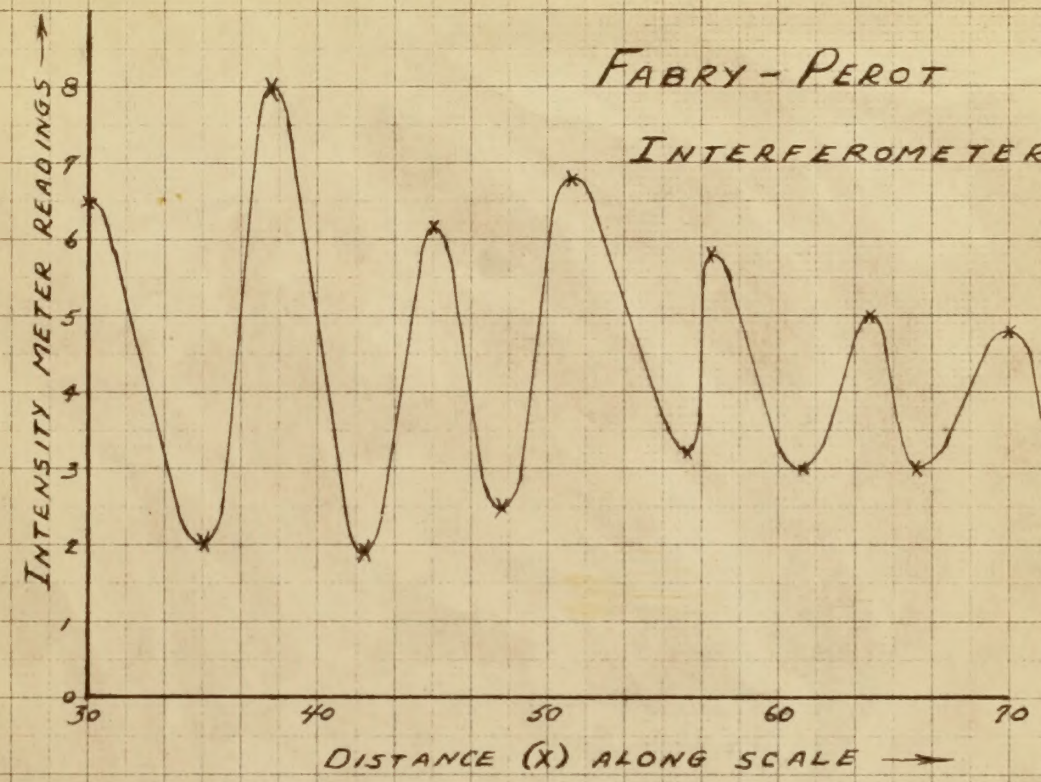
where d = the distance moved by the mirror.

and n - the number of fringes (maxima) observed to pass in the distance d.

Posit of (b)	Number of fringes passed in the distance moved by (b)
70.0	
-32.0	= 7
38,0 = d	

$$\lambda = 2d/n = 76/7 = \lambda = 11 \text{ cm.}$$

The graph of the results show clearly the presence of interference fringes. The wave-length, as calculated, is slightly in error. This is probably largely due to the relatively small number of readings that can be taken in a reasonable space because of the largeness of the wave-length. In theoptical case, the movement of one semi-reflector only a few centimeters would produce many thousands of fringes.


FABRY-PEROT
INTERFEROMETER
INTENSITY METER READINGS →
0
1
2
3
4
5
6
7
8
30
40
50
60
70
DISTANCE (X) ALONG SCALE →

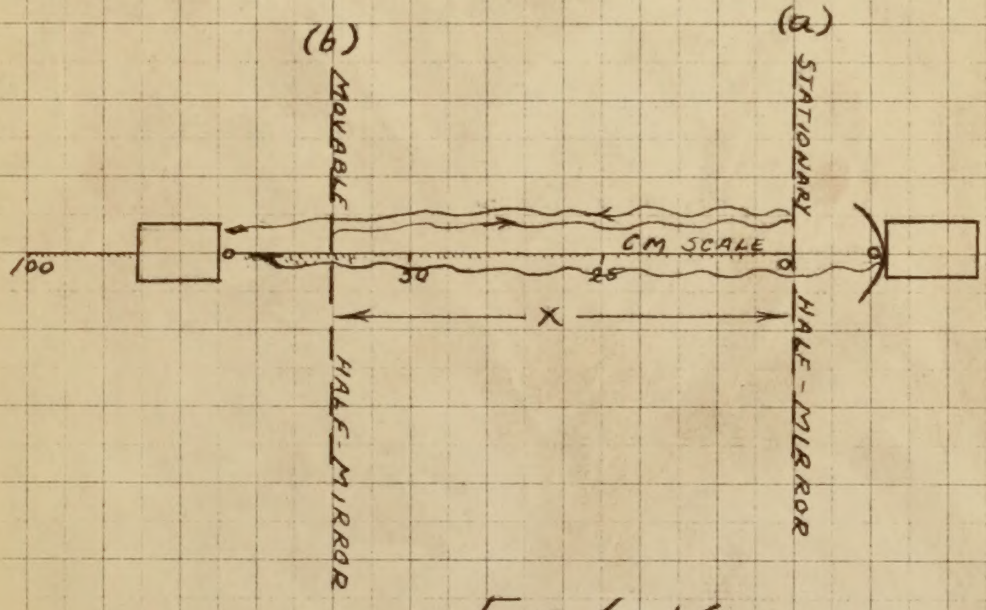

(b)
MOVABLE
(a)
STATIONARY
CM SCALE
100
30
25
X
HALF-MIRROR
HALF-MIRROR

FIG 6-16

XIII. MICHELSON INTERFEROMETER

The microwaves were broken into two segments by a semi-reflector in front of the transmitter. One part of the waves was transmitted to mirror (b) (see Figure 6-17) and reflected back to the half-mirror and reflected from there to the microammeter. The other part of the waves was reflected to mirror (a) by the half-mirror and then reflected back through the half-mirror or semi-reflector to the meter. These two beams intersected to produce interference at the meter. Whether the interference was constructive or destructive depended on whether the path difference between the two paths was some multiple of even $\frac{1}{2}$ wave-lengths (constructive) or some multiple of odd $\frac{1}{2}$ wave-lengths (destructive).

Reflector (a) was moved slowly and the meter readings were noted and recorded.

The wave-length of the microwaves can be determined from the equation (given in section XII) for the Michelson interferometer.

$$2d = n\lambda$$

Posit of (a)

89.0
71.0
18.0 = d

Number of fringes passed over in the distance moved by (a)

=4

$$\lambda = 2d/n = 36/4 = 9.0 \text{ cm.}$$

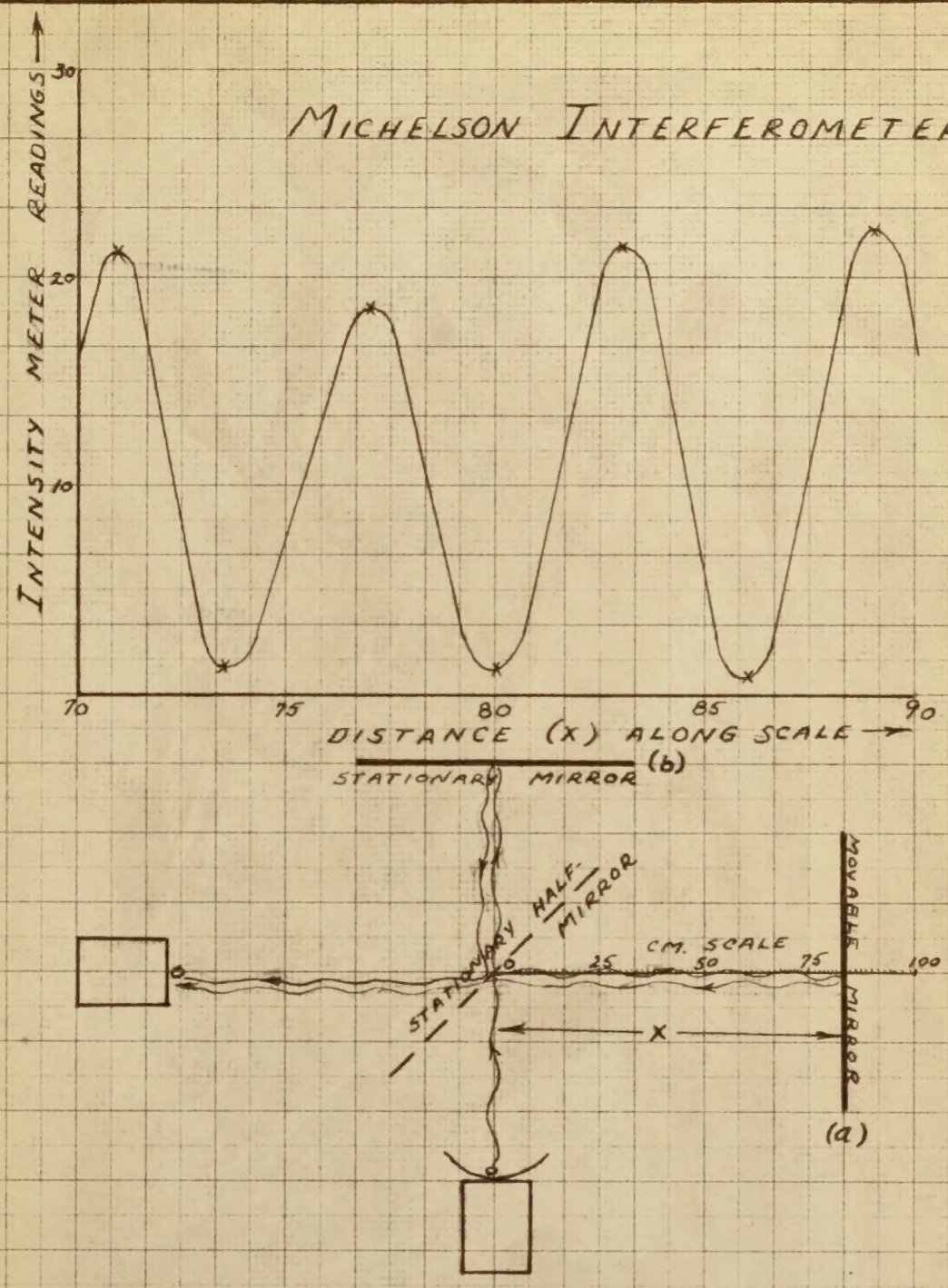

MICHELSON INTERFEROMETER
INTENSITY METER READINGS
30
20
10
70
75
80
85
90
DISTANCE (x) ALONG SCALE
STATIONARY MIRROR
(b)
HALF-MIRROR
STATIONARY
MOVABLE MIRROR
CM. SCALE
0
25
50
75
100
x
(a)

FIG. 6-17

The graph of the results (Fig. 6-17) shows the presence of an interference pattern. However, the calculation of the wave-length is in some error. This is, again, probably largely due to the small number of readings that could be taken in a limited space.

Qualitative results with this experiment are descriptive, however. A slight movement of the screen of one of the reflectors (in the realm of a millimeter) will produce a visible change in the reading of the microammeter.

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ABSTRACT

I. MICROWAVES

Microwaves are electromagnetic waves of wavelength 30 centimeters or less. They are produced by a number of special diode tubes in connection with a resonant cavity which can be considered to function like a tank circuit. One sucessful type of microwave producing tube is known as a "lighthouse" tube. It is able to produce high-frequency vibrations because the elements are placed very close together and the distance the electrons have to travel is so small that the plate does not change phase before the electrons arrive.

Microwaves are transported sucesstully by two systems. One is coaxial cable which is much the same as a parallel wire transmission system except that no energy can penetrate the outer conductor and thus no "radiation" can take place. The other system of transporting microwaves is by waveguides or hollow pipes. Waveguide transmission is best understood when it is discussed in terms of the electric (E) and magnetic (H) vectors of the transmitted wave rather than in current and voltage.

Microwaves are received from, and transmitted

into, space by means of antenna systems. Most antenna systems are composed of a half-wave dipole radiator and a parabolic reflector. This is not the only means of transmitting microwaves however, open and slotted waveguides have been used and are being developed now as sucesstul radiating systems.

II. MICROWAVE OPTICS

Microwave optics in one of the newer and more actively investigated fields of electronics. It is being developed as a valuable tool in research in many different fields of the physical sciences. However, to us, microwave optics has a basic meaning. It is a means of demonstrating optical principles which are difficult to explain. The apparatus necessary to perform most of the desired experiments consists of 3 two foot square wire screens; the small, compact microwave generator; and the small and hardy microwave intensity meter.

With the apparatus that was used in performing the experiments for this paper, many experiments such as the principle of the Michelson Interferometer experiment can be shown graphically to an entire class at once, with little "pre-class" effort and at a small cost. The apparatus, while not designed for quantitave work, can

be used for laboratory experimental work. It requires little experimental proficiency to operate, and would be useful as an introductory and supplementary source of optical experiments.

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